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Emission Factors for new and upcoming technologies in road transport

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Abstract

This report makes a review of historic emission control regulation from road vehicles in Europe, including conventional air pollutants and greenhouse gases. It then links these historic phases with new and upcoming regulations. The emission regulations have largely dictated the emission control technologies which are used in today's vehicles. Based on this, the report makes an outline of which are the new vehicle technologies and, based on literature values, suggests emission factors that can be used for urban, rural, and highway driving. The report ends with an assessment of the remaining environmental problems and the uncertainties related to the emission factors proposed.

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Executive Summary

Transport exhaust emissions play a major role in air quality problems that European cities are currently facing. Road vehicles contribute to an increase in the ambient concentrations of both ozone and particulate matter, representing the primary concern for urban air quality and directly threatening human health. The implementation of increasingly stringent vehicle emission limits and GHG reduction targets in Europe created an extremely dynamic environment, fostering road vehicle technology development. Several new solutions, including combinations of individual technologies, are proposed in every model year in order to fulfil requirements on both fronts. Due to this variety of technologies on the market, quantifying the impact of road vehicles to total emissions becomes an increasingly demanding task.

The objective of the present report is to provide emission factors for vehicle technologies that recently appeared on the market and for those that are expected to emerge in the near future. Background information about environmental regulations for road vehicles in Europe is provided as introduction to the technology assessment. Considerations range from past and current strategies to future trends and their impact on vehicle technology development. Based on the review of emission control regulations, a selection of new and upcoming vehicle technologies to be addressed in the report is presented. Table ES 1 lists vehicle types considered in the report.

Table ES 1. Vehicle types and technology coverage

VEHICLE TYPES	NEW Technologies	UPCOMING Technologies	UPCOMING Technologies
LDV	(PCs and LCVs)	Gasoline Euro 6 Diesel Euro 6 Hybrid Alternative fuelled	Euro 6c cars Battery and Fuel Cell
HDV	(trucks and buses)	Diesel Euro VI EEV Buses	
L-category	(mopeds, motorcycles, tricycles, quadricycles)	Gasoline Euro 3 Diesel Euro 3	Gasoline Euro 4/Euro 5 Diesel Euro 4/Euro 5

The report first provides aggregated emission factors (EFs) for the vehicle technologies in compliance with the latest emission standard at the time of writing. Emission factors were determined based on existing data, for the following range of selected pollutants:

- Regulated pollutants (CO, THC, NO_x, PM, PN).
- Non-regulated pollutants (NH₃, NO₂).
- Greenhouse gases (N₂O, CH₄).

Emission factors for the identified upcoming technologies are then presented. A final discussion addresses the role of battery electric vehicles, fuel-cell vehicles, and of next generation fuels.

The proposed EFs aim at representing a coherent set of emission factors that can be used to estimate average real-world emission levels, and therefore do not reflect the level of detail provided by several emission models. Generally speaking, road vehicle emission factors are always subjected to large uncertainties due to the high variability of operational and environmental conditions. The following general considerations apply to the uncertainties related to the proposed values:

- **Regulated pollutants for current vehicle technologies:** EFs are known with good confidence ($\pm 30\%$ of the mean value proposed).
- **Unregulated pollutants:** EFs are known with less certainty and are mostly designed to give an order of magnitude level of the vehicle emissions.
- **Future vehicle technologies:** EFs are estimates only based on the emission limit reductions and expected technological developments.
- **Relative trends:** the qualitative relative impact (increase or decrease of emissions) when shifting from one technology or fuel to the other is reliable.

The report ends with an assessment of the remaining environmental problems that current practices and upcoming vehicle technologies may entail

- Liquefied petroleum gas (LPG) and compressed natural gas (CNG) retrofits are currently approved by authorities only based on their safety and on simplified emission tests. Evidence has shown that malfunctioning of the lambda sensor is often associated with the use of an alternative fuel, consequently deteriorating the performance of the emission control system. Therefore, more checks on retrofitted vehicles are required and depending on the extent of the problem, specific interventions need to be planned.
- There is evidence that some diesel deNO_x aftertreatment systems currently employed may substantially increase N₂O emissions. Even if emitted in relatively small quantities, N₂O significantly contributes to total GHG emissions from individual vehicles given its nearly 300 times CO₂-equivalence. Including N₂O emissions in the total GHG vehicle policy budget is therefore necessary.
- Ammonia (NH₃) is controlled at present only for heavy duty vehicles equipped with SCR. Equivalent provisions are needed for SCR equipped light duty vehicles as well. Ammonia from gasoline vehicles is also largely unknown and may potentially constitute a significant environmental problem.
- Particle number (PN) emission control is nowadays well established in Europe for all compression ignition vehicle types and gasoline direct injection ones. The strict limits enforced from 2017 on should guarantee effective control of solid particles for those vehicle types falling under this regulation. Nevertheless concerns still remain on the non-solid particulate phase, which is not regulated by the current European PN emission control policy.
- Several pollutants for which air quality limits exist or for which there is a known toxic character still remain uncontrolled. As a result, limited or even no information is available and the contribution of road transport to ambient concentrations of these pollutants may be misjudged.

Despite the considerable research efforts to understand, monitor and control vehicle emissions, still significant unknowns are left. These come from the variety of technologies and fuels on the road, the frequent technology turnover and the range of environmental and driving conditions that vehicles operate in. Further efforts are needed to develop more reliable emission factors in order to improve emission inventories, understand and predict urban air quality hotspots and, in the end, design more effective policies.

1. Introduction

1.1. Air quality and climate change

European cities continue to face persistent air quality problems, primarily related to ozone (O₃) and particulate matter (PM). The latest assessment by the European Environment Agency (EEA, 2013a) reveals that some 20-30 % of the European urban population is exposed to average ambient levels above the European Union (EU) reference values for those two pollutants alone. This increases health risks primarily associated with cardiovascular and respiratory disease.

Transport exhaust emissions contribute to the ambient concentrations of both these pollutants. Road vehicles alone are responsible for 39% of total nitrogen oxides (NO_x) and 15 % of fine particulate matter (PM_{2.5}) emissions produced by anthropogenic sources in Europe in 2012 (EEA, 2014). Fine PM is defined as the mass of PM with aerodynamic diameter less than 2.5 µm and is linked to a number of health effects to humans (HEI, 2002). NO_x corresponds to the prime pollutant related to ground-level ozone formation and road transport is the single most important source.

Most importantly, the operation of vehicles within the urban environment increases the relative risks due to the proximity of human activities with the emission sources and the direct exposure to the pollutants produced. Ambient concentrations at monitoring stations primarily affected by road vehicles exceed typical urban levels by several times (EEA, 2013c). Several studies have shown that human exposure to pollution in urban areas is often dominated by road vehicle emissions (HEI, 2010). Because of the proximity and direct exposure to air pollutants produced by road traffic, any reduction of emissions from vehicles should lead to higher health benefits than by proportionally reducing the average urban concentration levels.

In order to address these issues, reductions in emissions of road vehicles have been taking place in Europe since the beginning of the 1970s with the introduction of consecutively stringent emission standards. These standards, widely known as “Euro” standards, have been setting lower emission limits for an increasing number of pollutants with time. Compliance with the decreasing emission limits is achieved through the gradual implementation of enhanced emission control technologies, comprising both in-cylinder combustion measures and aftertreatment technologies.

A more recent development related to vehicle emission regulation has been the control of greenhouse gas (GHG) emissions, primarily by reducing fuel consumption and secondarily by the introduction of renewable energy in transport. Those measures aim at decreasing the share of road transport to total greenhouse gas emissions, which today reaches ~23 % of total GHG emissions in Europe (EEA, 2013e), in order to meet the EU targets on combating climate change. EU has established fleet-average numerical targets for CO₂ emissions from passenger cars (EU, 2009) and light commercial vehicles (EU, 2011) while emission labelling for heavy duty vehicles is underway. The recent emission evolution trends for passenger cars suggest significant CO₂ emission reductions over the certification procedure. The average new passenger car produced 132 g CO₂/km in 2012 compared to 167 g CO₂/km, one decade ago, which corresponds to approx. 2 % annual improvement in CO₂ emissions (EEA, 2013d).

1.2. New technologies in road vehicles

The combination of air quality limits on one hand and GHG reduction targets on the other creates a very dynamic environment for road vehicle technology evolution.

There are different strategies that are being followed by vehicle manufacturers and fleet operators to achieve combined reductions in both fronts. The first very popular strategy is to use conventional technology gasoline or diesel vehicles where enhanced emission control technologies are introduced to meet the emission limits. Then, separate technology measures are taken to address fuel efficiency. Several times, low air pollutant emission requirements introduce a fuel penalty, which has to be counterbalanced by more advanced efficiency improvement measures. A typical example is the introduction of diesel particle filters (DPFs) on passenger cars, which are known of increasing fuel consumption due to the backpressure in the exhaust line and the need for extra fuel to initiate regeneration (for light duty vehicles).

The second strategy has been to primarily address efficiency targets by introducing enhanced combustion technologies and then by developing emission control technologies particularly adapted to the new combustion concepts. A typical example of this strategy has been the introduction of direct fuel injection in gasoline vehicles, which is an advantageous concept in terms of energy efficiency, compared to conventional gasoline combustion. However, special attention is required for NO_x control and, in the future, for PM control of these vehicles.

The third strategy has been the introduction of new energy carriers, as alternatives to either the gasoline or diesel fuelled vehicles. Some of these energy carriers have the potential to achieve reductions in both GHG and air pollutants. A typical example of such a strategy includes the use of electricity in hybrid vehicles or the introduction of (locally) zero emission electric vehicles. Other alternative energy carriers with potential in both the air pollutant and GHG fronts may include natural gas, biofuels, etc.

Each of these strategies may be adopted either individually or in combination with other strategies by each manufacturer. As a result, a multitude of combinations of individual technologies appear on the market every year to fulfil the same emission limit and greenhouse gas targets. Just to put this into perspective, each legacy Euro standard was associated with a single emission control technology per vehicle type. Today, three different main emission control technologies exist for Euro 6 cars, either of the diesel or of the gasoline type (six in total). On top of this, various versions of electrified and bi-fuelled vehicles explode the number of possible combinations. Due to this variety of technologies on the road, quantifying the impact of road vehicles to total emissions becomes an increasingly tedious task.

1.3. Objectives and structure of the report

The report aims at providing emission factors for a variety of new technologies that have recently appeared on road vehicles and for emission technologies that are expected to appear in the near future. The emission factors proposed are based on analysis of existing data and no new emission data have been generated for this study. The intention has been

to generate a coherent set of emission factors that can be used to estimate average real-world emission levels of current and upcoming vehicles. Hence, the emission factors proposed do not go into the detail that several of the emission models go but aim at reflecting typical emission levels.

In developing and assessing these emission factors, this report is structured as follows, further to this introductory chapter:

- Chapter 2 provides an overview of the environmental regulations for road vehicles as background information, ranging from the historic to recent years and the foreseeable future. The environmental regulations foreseen determine to a large extent the emission control technologies that will appear and, as a result, the expected emission levels of future road vehicles.
- Chapter 3 presents the methodology that has been followed to develop the emission factors and justifies the selection of vehicle types and pollutants considered in the report.
- Chapter 4 presents a description of the emission control technology and the associated emission factors for each of the recent (new) vehicle types considered.
- Chapter 5 attempts an assessment of the technology and the associated emission levels for niche vehicle types and fuels which are expected to become more popular in the future.
- Finally, Chapter 6 makes an overall assessment of the emission factors proposed with a discussion on uncertainties and priorities for improvements.

2. Environmental Regulation for Road Vehicles

2.1. Light Duty Vehicles

2.1.1. First period: The early years

Automotive emissions have been regulated in Europe since 1970 with the implementation of the parent European Council Directive 70/220/EEC. This Directive has been the result of an intensive period of consultation between member countries of the European Economic Commission (EEC) at that time, in their effort to develop a common European environmental policy for road transport emissions. Educative descriptions of the approach and the hurdles faced to build a common European policy in these starting years are presented by Berg (2003) and Friedrich et al. (2000).

The technical details of the automotive emission control policy were mostly discussed by designated experts within the activities of the United Nations Economic Committee for Europe (UNECE). In the beginning of the 1970s, UNECE established Regulation 15 which, together with its various amendments, delivered the first coherent automotive emission control policy in Europe for vehicles with masses less than 3.5 tonnes. The different steps and implementation years of the UNECE R15 regulation are shown in Table 1.

Table 1. Emission control steps implemented with regulation UNECE R15

Step	Implementation years
ECE-R15/00 & 01	1971 to 1977
ECE-R15/02	1978 to 1980
ECE-R15/03	1981 to 1985
ECE-R15/04	1985 to 1992

The implementation dates shown in Table 1 were approximate for each of the member states at that time. National parliaments had to ratify the individual steps of the Regulation which meant a somewhat differentiated implementation date in each country. The first step of this regulation introduced only carbon monoxide (CO) and hydrocarbon (HC) emission limits for gasoline vehicles. ECE-R15/02 was the first to introduce a NO_x emission limit while ECE-R15/04 extended the legislation to also cover diesel vehicles.

In a parallel effort to cover heavy duty applications as well, Council Directive 72/306/EEC provided maximum opacity limits for all diesel engines used in automotive applications. This was considered as an implicit and simplified approach to control smoke emissions from engines. No definition or control targets for PM existed at that time.

In the period between 1985 and 1992, a number of additional steps appeared in several countries, in an effort to accelerate the introduction of advanced vehicle technology by some member states. This was because local air quality problems were mounting and the

increased pressure from the public to bring additional emission control contrasted the slow and bureaucratic process at a European level. Hence, improved combustion measures – the so called “improved conventional” vehicles appeared in Germany (Attachment XXIV) and in the Netherlands (NLG850). Thereafter, but certainly before 1992, several countries (Denmark, Germany, Greece, Netherlands) also enforced the “open loop” catalytic control. With this, a three way catalyst and stoichiometric combustion were implemented. However, no lambda sensor was used to adjust stoichiometry in actual operation. Rather, map-based fuel mixture preparation was enforced. This technology could not effectively control emissions over transients but could adequately reduce NO_x and oxidize CO and HC under most cruise conditions.

2.1.2. Second period: Two decades of maturation

This first period in automotive emission control ended with the implementation of Directive 91/441/EEC in 1992 across Europe. This regulation was the first to introduce the currently well-known “Euro” emission norm, starting with the “Euro 1” step. Among others, this introduced the mandatory use of the closed-loop three way catalyst (TWC) for gasoline vehicles and PM emission control for diesel vehicles. The closed-loop catalytic control was really a technology breakthrough, which was first implemented in the USA. The engine could self-calibrate itself during operation hence effectively controlling all three major pollutants (CO, HC, NO_x) under basically all conditions. The same technological concept, only improved in its implementation, is still used in all gasoline cars produced around the world today.

This was followed one year later by Regulation 93/59/EEC which implemented similar emission limits for light commercial vehicles (LCVs). Different Euro steps followed in the coming years, introducing the Euro 2, Euro 3 and Euro 4 standards with increasingly stringent emission limits. These four steps together covered almost two decades of emission regulation (1992-2010). Otherwise, no significant changes in the regulatory approach and the structure of environmental policy took place in this period.

Table 2. Emission control steps for LDVs implemented in Europe in the 1990s and 2000s

Stage	Passenger Cars		Light Commercial Vehicles	
	Implementation dates	Legislation	Implementation dates	Legislation
Euro 1	07.1992-12.1995	91/441/EEC	10.1994-12.1997	93/59/EEC
Euro 2	01.1996-12.1999	94/12/EEC	01-1998-12.1999(N1-I) or 12.2000 (N1-II/III)	96/69/EC
Euro 3	01.2000-12.2004	98/69/EC	N1-I: 01.2000-12.2004 N1-II/III: 01.2001-12.2005	98/69/EC
Euro 4	01.2005-08.2009		N1-I: 01.2005-08.2009 N1-II/III: 01.2006-08.2010	

The implementation dates in Table 2 refer to new vehicle types, with the same emission steps applicable to all vehicle types by one year later.

2.1.3. Third period: New momentum in regulations

The third phase in light duty vehicle emission control came about with the activities focusing on the introduction of the Euro 5 and more recently of the Euro 6 emission control steps. These two steps have been linked with a renewed interest in automotive emission control, as a result of a combination of reasons:

1. Despite the many steps in automotive emission control, a large fraction of Europe's population continues to live in environments that exceed acceptable air quality limits (EEA, 2013a) and, therefore, further action is still needed.
2. Diesel cars in particular have been shown to substantially exceed their corresponding NO_x emission limits in real world operation, e.g. Weiss et al. (2011a); Weiss et al. (2011b). This trend, if continued, jeopardizes every effort to meet air quality targets in Europe (Borken-Kleefeld and Ntziachristos, 2012).
3. Increasing concerns on the health effects of particulate matter emissions have accumulated pressure for their drastic reduction (Frampton et al., 2013).
4. The challenging targets on improving vehicle fuel consumption efficiency, first introduced for passenger cars with Regulation 443/2009/EC, mean that the repercussions of efficiency targets to emission control have to be considered.

As a result of this challenging environment, several regulations and directives have been already published to bring to the market vehicles that consume less and emit less under real-world conditions. Table 3 provides a summary of the main pieces of regulation regarding the emission control and fuel efficiency of light duty vehicles that have appeared within the same period of implementation of the main Euro 5 and Euro 6 regulations.

The various requirements included in the regulations summarized in Table 3 are implemented in the Euro 5 and 6 stages gradually, hence creating a sub-distinction to more steps within each regulatory stage. This sub distinction is presented in Table 4.

The first new element introduced with Euro 5 was the control of solid particle emissions from both diesel and gasoline direct injection cars and vans. The procedure and the emission limits set have been based on a multi-national effort conducted within the Particle Measurement Programme – PMP (Giechaskiel et al., 2010). Euro 5 and Euro 6 diesel vehicles need to emit below $6 \times 10^{11} \text{ km}^{-1}$ particles while a two-step approach has been decided for Euro 6 direct injection gasoline vehicles to allow enough lead time for technology development. A first step calls for a $6 \times 10^{12} \text{ km}^{-1}$ limit (Euro 6b) while a second, decreased limit, at the same level with diesel cars is introduced with the Euro 6c step.

These two regulatory stages have also put a lot of emphasis on the implementation of OBD systems. Although OBD has been an indispensable element of emission control since Euro 3, the focus at a Euro 5 and predominantly at a Euro 6 step has been on introducing appropriate OBD threshold limits (OTLs) and In-Use Performance Ratios (IUPRs). The thresholds are emission levels – expressed as equivalent values over the type approval test – an exceedance of which should illuminate the Malfunction Indicator Lamp (MIL). In this way the driver is informed that the vehicle emission control is suboptimal and that a service check or maintenance is required.

Table 3. Summary of vehicle emission control and energy efficiency regulations that have appeared in the post Euro 4 LDV era

Regulation	Content
715/2007	Introduction of the regulatory framework for Euro 5 and Euro 6 light duty vehicles
2007/46	New regulation on how vehicle type approval has to be conducted and what this should contain
692/2008	Euro 5 & 6 technical implementation procedures and modalities
79/2009	Extension of the type approval procedure to include H ₂ vehicles
443/2009	Specific targets on average CO ₂ emissions from new sales of passenger cars up to 2020
661/2009	Mandatory implementation of Gear Shift Indicators (GSIs) and Tyre Pressure Monitors (TPMs) on cars
406/2010	Technical implementation and procedures for the type approval of H ₂ vehicles
510/2011	Specific targets on average CO ₂ emissions from new sales of light commercial vehicles up to 2020
566/2011	On-board diagnostics (OBD) monitoring and implementation and in-service conformity testing for Euro 6
725/2011	Certification of eco-innovations
65/2012	Technical implementation and procedures for GSIs
459/2012	Introduction of particle number limits for GDIs and OBD thresholds for Euro 6 vehicles
195/2013	Introduction of eco-innovations as part of the type approvals and calculation of the CO ₂ benefits

Table 4. Intermediate stages in the Euro 5 and Euro 6 LDV regulations

Designation	Description	Engine Concept	Type of registration	M & N1-I	N1-II & III	Notes
Euro 5a	Reduced emission limits, Euro 4 PM sampling procedure, no PN limit, base Euro 5 OBD requirements w/o IUPR monitoring	PI, CI	New Types	1.9.2009	1.9.2010	
			New Vehicles	1.1.2011	1.1.2012	
Euro 5b	Full Euro 5 emission requirements including revised measurement procedure for particulate matter, particle number standard for CI vehicles and flex fuel vehicle low temperature emission testing with biofuel. Relaxed IUPR included for OBD monitoring	PI, CI	New Types	1.9.2011		New vehicles in 2013 sold w/o need for IUPR monitoring
			New Vehicles	1.1.2014		
Euro 6a	Euro 6 limits with Euro 4 PM sampling procedure	CI		latest registration by 31/12/2012		Aiming to assist incentives programmes and early adoption schemes
Euro 6b	Euro 6 emission requirements including revised measurement procedure for particulate matter, first step of PN limit for PI vehicles and flex fuel vehicle low temperature emission testing with biofuel. Preliminary OBD thresholds and relaxed IUPR limits	PI, CI	New Types	1.9.2014	1.9.2015	
			New Vehicles	1.9.2015	1.9.2016	
Euro 6c	Full Euro 6 emission requirements, including second step in PN limit for PI vehicles. Final OBD thresholds and IUPR monitoring	PI, CI	New Types	1.9.2017	1.9.2018	
			New Vehicles	1.9.2018	1.9.2019	

The IUPRs are virtual counters that check whether the on-board diagnosis occurs with a minimum acceptable frequency, during the vehicle's operation. In principle, OBD can take place only within given operational and environmental conditions, in order to be able to infer equivalent type-approval test values from momentarily measured emission levels. IUPRs guarantee that diagnosis actually occurs at a minimum rate when such operation conditions are met. This is to eliminate too infrequent diagnosis that would result to too long times to identify exceedances. Relaxed OTLs and IUPRs were enforced at a Euro 5 level that later became more stringent at a Euro 6 limit.

Several other requirements were added or modified in the transition from Euro 4 to Euro 5 and Euro 6. Durability requirements of emission control devices has been extended to 160000 km with revised deterioration factors and mileage accumulation tests (Galassi and Martini, 2014), definition of procedures for flexi-fuel vehicles, inclusion of updated specifications for reference test fuels, including biofuel blends, etc.

At the same time with all these emission control regulatory improvements, fuel-efficiency specific targets, and by that CO₂ emission targets, were set independently for cars and vans. The specific targets, together with the latest historical data for cars are shown in Figure 1. Specific targets for cars were introduced by Regulation 443/2009 while van CO₂ emissions are addressed by Regulation 510/2011. The targets include a first level at 175 g CO₂/km to be phased in from 2014 and to be fully reached in 2017 and 147 g CO₂/km to be reached in 2020. For the intermediate years, super-credits are given for cars and vans that emit below 50 g CO₂/km, to accelerate the introduction of vehicles with extra low emission levels. An additional component of the regulation is the introduction of eco-innovations, i.e. further allowances for devices or techniques that deliver actual CO₂ emission reductions on the road, which cannot be demonstrated during the type-approval test. Examples of such approaches include efficient lighting systems, solar panels implemented on the vehicle, etc. A maximum allowance of 7 g CO₂/km per manufacturer can be provided by eco-innovations.

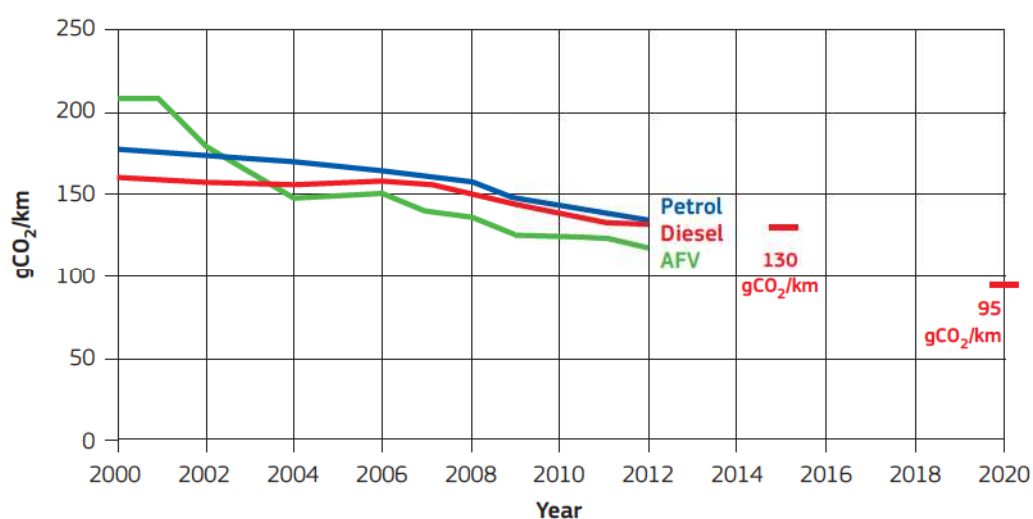


Figure 1. New cars average CO₂ emission evolution and future targets according to 443/2009/EC (EEA, 2013b)

2.1.4. What the future may bring

Although the general framework for the regulation of Euro 5 and Euro 6 cars has been set with the existing legal documents, there are significant new regulatory components in the pipeline. An important development is the replacement of the New European Driving Cycle (NEDC) by the Worldwide harmonized Light vehicles Test Procedure (WLTP). WLTP has been developing since 2007 within the activities of the UNECE Working Party on Pollution and Energy (GRPE), and “aims at providing a worldwide harmonised method to determine the levels of gaseous and particulate emissions, CO₂ emissions, fuel consumption, electric energy consumption and electric range from light-duty vehicles in a repeatable and reproducible manner designed to be representative of real world vehicle operation” (UNECE, 2013).

When finalized, the new driving cycle proposed as well as the methods and approaches agreed within WLTP will need to be transposed to the European Regulations. This is planned to be phased in until the 2017/18 horizon, i.e. together with the implementation of the final Euro 6c (Table 4) step. The new procedure makes provisions for a number of technical details regarding the type approval procedure, with the aim to develop conditions that more representatively approach the real operation of the vehicle on the road. These provisions include a new driving cycle, new definitions and settings for the vehicle inertia, preconditioning and soak procedures, etc. The intention is primarily to end up with fuel efficiency and CO₂ values that better approximate the levels reached during real world vehicle operation.

Admittedly, the most important component of the new regulatory package for conventional pollutants is that compliance with the emission limits needs to be demonstrated over real world vehicle operation. Pollutants measurements will be done on board the vehicles, using PEMS – Portable Emission Measurement Systems (Weiss et al., 2011a), so that the Real Drive Emissions (RDE) of the vehicle are revealed (Weiss et al., 2013). The new approach should define boundary operational and environmental conditions where distance-specific emissions have to be calculated, using the average window concept. In this, consecutive windows of distance equal to the type-approval test are identified and pollutants emissions are integrated over these windows. These distance-specific pollutants should be, within a flexibility margin, below the emission limit value. The new approach will complement the measurement of emissions over the WLTP, so that a thorough emission control is achieved in the lab but also on the road.

The real-drive emissions concept will need to cover both gaseous and particulate emissions, including particle number measurement. This is challenging, as no verified technique to measure particle number on the vehicle has been established yet. New concepts and approaches are being developed in the 2013/2014 period including electrical detection of the aerosol in real time combined with constant flow sampling (Riccobono et al., 2014).

The discussion on particle number regulation also extends to whether the cut size at 23 nm, which has been established as the lower limit for particle number detection (Giechaskiel et al., 2010), remains appropriate or not. The concerns arise from mounting evidence that the exhaust of gasoline direct injection vehicles contains a significant fraction of particles below 23 nm (Mamakos et al., 2013a), hence a rather large part of total particulate emissions remains uncontrolled. The decision as to whether this will have to change will depend on a variety of parameters, including availability of appropriate sampling techniques, the use or

not of a gasoline particle filters to meet emission limits at a Euro 6c level, and the overall cost-effectiveness of changing the regulatory requirements.

The new WLTP also makes technical provisions for the regulation of pollutants which are not included in the existing legislation, such as aldehydes, NO₂, and N₂O, and others. It is not currently clear if, when and how these are going to be transposed to the European regulations. Obviously, introducing the control of additional pollutants will have repercussions to the technology that is going to be used to meet the levels enforced.

In terms of efficiency and CO₂ emissions improvements, targets for the post-2020 era will have to be defined, including fleet-average CO₂ levels, the exact implementation of super-credits and eco-innovations, the need for separate targets and assessment of new biofuels, etc.

Before reaching this point, the translation of the NEDC-based 2020 targets to the new WLTP will have to be conducted. This is a complicated and challenging procedure because this does not translate to the adjustment of the emission limits for a single vehicle but to the complete range of vehicles produced by each manufacturer. In order to retain equivalency to the NEDC-based targets, one has to consider the mix of technologies that each manufacturer has in the pipeline and to assess their impact on the WLTP/NEDC ratio. The exact translation will have significant repercussions to the technologies that will be promoted in the future. One characteristic example is that the much smaller contribution of idle over the WLTC (13.4 % of the duration of the cycle) than over the NEDC (22.6 %) means that the impact of start and stop systems on achieving low CO₂ emissions will fade out when the WLTP is introduced. Hence, new approaches in efficiency improvement when the WLTP is introduced are to be expected.

2.2. Heavy Duty Vehicles

2.2.1. First period: Five emission steps by two regulations

Traditionally, heavy duty vehicles, including trucks and buses, have been powered by diesel engines owed to their high efficiency, robustness and serviceability. Due to the large size of these vehicles but also because a rather small number of engine families are implemented in heavy duty vehicle series of each manufacturer, emission regulations have been built around the engine concept. That is, the engine is type-approved with respect to its energy specific emissions by connecting it to a dynamometer, which simulates road load and applies this to the engine.

Heavy duty diesel engines were historically controlled for their smoke levels using an opacimeter, as specified by Council Directive 72/306/EEC, on steady state and free acceleration tests. The legislation imposed maximum limits for the emission of visible smoke. The first gaseous pollutants limits were developed by UNECE in 1982 with the development of Regulation 49 which set the techniques and limits for the control of CO, HC and NO_x. The work at UNECE was later taken up by the European Council Directive 88/77/EEC, which first established mandatory limits for new types of on-road diesel engines with regard to their gaseous emissions. A new operation cycle (ECE-R49), consisting of 13 operation points and appropriate weighing factors was introduced to allow an enhanced coverage of engine operation.

This piece of legislation came before the establishment of the “Euro” standards – which was mostly introduced as a terminology with the introduction of the light duty emission standards. However, this emission stage was ex post designated as “Euro 0” (see Table 5).

Table 5: Historic emission control steps implemented for heavy duty engines

Step*	Enforcement date New Types	Enforcement date New Engines	Regulation
Euro 0	01.07.1988	01.10.1990	88/77/EEC
Euro I	01.07.1992	01.10.1993	91/542/EEC Stage A
Euro II	01.10.1995	01.10.1996	91/542/EEC Stage B
EEV	No enforcement – acceptance by 01.07.2000		1999/96/EC
Euro III	01.10.2000	01.10.2001	
Euro IV	01.10.2005	01.10.2006	
Euro V	01.10.2008	01.10.2009	

* Roman numbering is used by convention for Euro standard distinction of heavy duty vehicles/engines, in contrast to Arabic numbering used for light duty vehicles.

Directive 91/542/EEC established the first two “Euro” based emission limit stages for heavy duty engines (Euro I and II), including the regulation of PM emission, as a consequence of the intensive discussions within the activities of the Auto Oil I programme and follow up revisions by the European Council and the Parliament. These two stages aimed at bringing heavy duty vehicle emissions control on par with their light duty counterparts.

These earlier stages were followed by Decision 1999/96/EC which, in total, defined four new stages for heavy duty vehicle emission control, spanning from 2000 to 2014 (i.e. until the introduction of Euro VI) – Table 5. This was done on purpose in order to allow adequate lead time to the automotive industry to develop the necessary technology to meet the agreed emission limits. One significant concept introduced was the definition of Enhanced Environmentally friendly Vehicles (EEVs), i.e. a stringent voluntary emission stage introduced as early as in 2000. This step was more stringent even than the much later introduced Euro V. The rationale with its introduction was to provide a possibility for local governments facing tough environmental pressures to provide incentives for the introduction of super clean vehicles in their controlled captive fleets. EEV limits could be met only by gas vehicles or diesel vehicles with advanced exhaust aftertreatment devices.

The same directive also introduced several new test cycles for engines of different emission control technology. The European Stationary Cycle (ESC) and the European Load Response (ELR) procedure were introduced for the control of gaseous and particulate pollutants, and smoke opacity, respectively, of all Euro III diesel engines. On top of this, Euro III engines equipped with advanced aftertreatment and all Euro IV and Euro V engines had to be tested over the European Transient Test (ETC). Finally, gas engines had to be tested solely over the ETC.

2.2.2. Second period: Enforcing advanced aftertreatment technology

Directive 1999/96/EC provided a solid base to decrease emission limits of heavy duty engines up to a Euro V standard. In parallel, it made reference to additional requirements from heavy duty engines and vehicles, including durability, OBD monitoring, and in-use conformity. However, it introduced no technical provisions for any of these components. These came later with more focused pieces of legislation. Directive 2005/55/EC introduced durability and OBD requirements for heavy duty vehicles in two stages, the first one for Euro IV vehicles and the second for Euro V. EEVs were always updated to the latest OBD requirement. At the same time, Directive 2005/78/EC made the technical provisions for all these components. It also introduced measures for the monitoring of NO_x reagent quantity carried by the vehicle, for those vehicles specifically equipped with Selective Catalytic Reduction (SCR) systems. If the engine was allowed to operate without reagent, then torque limiters were enabled after the vehicle became stationary for the first time. The reagent should then be replenished for the engine to operate again normally. This was enforced to avoid intentional or unintentional operation of the vehicle for long without efficient NO_x aftertreatment operation. Several technical details related to the durability, OBD operation, and testing requirements were later improved with Directive 2006/51/EC (demonstration of the operation of the NO_x emission control monitoring system) and Directive 2008/74/EC (revision and inclusion of the smoke opacity test in the regulations).

The period in the change of the Comitology procedure within the European policy making, coincided with the discussion on the Euro VI emission limits for trucks. Regulation (EC) No 595/2009 introduced this new procedure and the emission limits at a Euro VI level became applicable since January 2013. It also made provisions for the inclusion of a particle number limit and the introduction of two new operation cycles for type approval, i.e. the Worldwide Harmonised Steady state Cycle (WHSC) and the Worldwide Harmonised Transient Cycle (WHTC). The transient cycle also introduced control of cold start emissions for heavy duty engines.

The first implementing act for this new regulatory framework came with Regulation (EU) No 582/2011. A completely new element introduced with this Regulation was the provision of on road complete vehicle testing using PEMS to demonstrate the in-service conformity of the engine or the vehicle. With this, the vehicle is measured on the road with a loading encountered in typical operation and over a variety of driving situations. Emissions of gaseous pollutants are then calculated using the “averaging window” principle, according to which the emissions are expressed as mass of pollutant per unit of work performed by the engine. Each averaging window is calculated so that the total work over this window is equal to the work performed by the engine over the reference transient driving cycle (i.e. WHTC). A window is considered valid if the average power in this window is at least 20 % of the maximum engine power, otherwise this particular window will have to be excluded from further consideration. Conformity factors are then estimated based on the ratio of the actual emission value over each window to the emission limit value. Conformity is granted if at least 90 % of these conformity factors do not exceed the emission limit by more than 50 %.

Other important items of the new regulation included numerical limits for emission control over WHSC and WHTC, including particle number, increased durability distances (reaching

700000 km for vehicles above 16 t), lower thresholds for PM and NO_x OBD monitoring, establishment of minimum accepted IUPRs ratios (at a value of 0.1), provisions for the measurement of CO₂ emissions and fuel consumption, and others.

The Euro VI stage was extended with Regulation (EU) No 133/2014 to dual fuel and gaseous fuel engines and vehicles. This also introduced a particle number limit for positive ignition engines.

2.2.3. The future for HD emission regulation

Euro VI has brought substantial changes in the regulation of heavy duty vehicles, enforcing DPF and SCR control practically to all of them for an efficient control of pollutants over a transient cycle, including cold-start. Moreover, the in-use conformity of the trucks is checked with the use of PEMS under real driving conditions. Together with durability requirements, these provisions make sure that emissions from such vehicles will be low and will remain low throughout the vehicles useful life.

One of the remaining issues in making sure that emissions will remain low throughout the useful vehicle lifetime is the effective operation of PM OBD systems. Regulation (EU) No 582/2011 requested that for all HDVs placed on the market post September 2015, a soot sensor placed on the exhaust line should guarantee that emissions remain below 25 mg/kWh downstream of the DPF. However, the same regulation clarified that this request is under review pending confirmation of the technical feasibility of the target. Latest evidence suggests that although the available soot sensors are of sufficient sensitivity to detect exceedance of the threshold, they still seem to suffer from durability issues that deem their mandatory installation on vehicles still problematic. It is therefore expected that this requirement will be postponed until the technical feasibility is confirmed.

In any case, the emphasis on OBD monitoring of low PM emission limits from HDVs makes clear that the control of particulate emissions over the lifetime of the vehicle is a priority within EU. Therefore, technological and regulatory developments in this area are expected to intensify in the future.

PM is also in the focus of in use compliance for heavy duty vehicles. A PEMS Pilot study is underway to demonstrate the applicability of a new measurement protocol for the measurement of PM emissions on board the vehicle. This pilot study is expected to end up to a new regulatory component of PM measurement.

Further to the control of air pollutants, monitoring and certification of HDV CO₂ emissions will also become mandatory in the coming years. HDVs, in contrast to passenger cars, exhibit a high variance in their CO₂ emissions, depending on their exact configuration. Use of the tractor with different trailers, variable consumption of their auxiliaries (e.g. fridge semi-trailers) and the large ratio of payload vs vehicle weight makes the type approval procedure adopted for passenger cars not appropriate for trucks. The pathway that has been decided for monitoring actual vehicles CO₂ emissions is by simulation of the vehicle topology and characteristics (European Commission Communication COM(2014) 285 final). In this way, a CO₂ value is assigned to the complete vehicle, taking into account all its individual characteristics, including aerodynamic performance, transmission configuration, engine efficiency, tyre specifications, etc.

It has not been decided yet how this information is to be used. Informing the customers and operators of the CO₂ emissions of a truck via labelling is expected to be important in reducing CO₂ emissions by suitable vehicle selection. Additional steps on monetary and regulatory approaches to achieve fixed targets on CO₂ emissions from heavy duty trucks cannot be excluded in the future.

2.3. Mopeds and Motorcycles

2.3.1. First period: Introduction of Euro standards

Mopeds and motorcycles have traditionally been significant emitters of HC and CO, owed to their engine and performance calibration (Ntziachristos et al., 2009a). In particular mopeds in the past have been powered by two stroke engines which have been notorious emitters of unburned hydrocarbons and, as a consequence, also of particulate matter (Spezzano et al., 2008; Spezzano et al., 2009), as a result of piston scavenging losses

The first efforts for the control of emissions of mopeds and motorcycles started with Directive 97/24/EEC that first introduced the Euro 1 stage for mopeds in 1999 (Euro 1). The Euro 2 moped stage became applicable by 2002. These stages introduced CO and composite HC+NO_x emission limits for mopeds over the ECE-47 cycle, a cycle of repetitive full load accelerations to maximum speed, constant speed driving at maximum speed and then a deceleration to idle with an intermediate step at 20 km/h. This has been a severe driving cycle but relatively well corresponding to the actual on-road driving profile of such vehicles. For this reason, the limit values enforced already at Euro 1, although relatively high compared to other vehicle types, led to the implementation of an oxidation catalyst for mopeds and the gradual migration from two-stroke to four-stroke combustion together with combustion improvements.

The same regulation also introduced the Euro 1 motorcycle step that enforced limit values separately for CO, HC, and NO_x. The rather relaxed limits in that case meant that no particular aftertreatment system had to be introduced, but improvements in the combustion process were sufficient to comply with the regulation requirements. Directive 2002/51/EC brought two additional regulatory steps for motorcycles, namely Euro 2 by 2003 and Euro 3 by 2006. The new standards required significant revisions to the engine and aftertreatment technology. In particular Euro 3 was made possible only with the introduction of electronic fuel injection, stoichiometric combustion, and a three way catalyst for the vast majority of four stroke motorcycles.

A significant development over this period has also been the introduction for the first time in all road vehicle categories of a global driving cycle, the Worldwide harmonized Motorcycle emissions Certification Test procedure (WMTC). The new driving cycle aimed at providing a common ground for the type approval of different vehicle types for all global markets. The Euro 3 motorcycle emission limits were adjusted to the new driving cycle with Directive 2006/72/EC.

2.3.2. Second period: Holistic approach

The second period of moped and motorcycle emission regulation was initiated already in 2002 with the open question whether PM emissions had to be separately regulated for mopeds and motorcycles (Rijkeboer et al., 2005). The argumentation against a separate PM control has been that reduction of HC would satisfactorily also bring PM down. Therefore, the discussion focused on further reducing gaseous emissions, rather than setting up a separate limit for PM.

The process of further reducing emissions from mopeds and motorcycles has been a long and complicated procedure that became fruitful in 2013 with Regulation (EU) No 168/2013, that introduced the Euro 4 and Euro 5 stages for mopeds and motorcycles. Also, in the same batch of measures, Directive 2013/60/EU introduced the Euro 3 stage for mopeds. This regulation package completely transformed the way that such small vehicles are perceived by the legislation. It introduced seven main classes of L-category vehicles, ranging from electric bikes to sub-M1 passenger cars, with individual sub types and variants (Figure 2). Different type approval requirements have been set for each of the individual vehicle types. This does not only include a customised driving cycle and different sets of limits for exhaust emissions, but also a range of other type approval requirements, including:

- Idle/free acceleration tests
- Durability of aftertreatment devices
- Fuel evaporation control
- Fuel and energy consumption measurement
- Crankcase emissions control

Most importantly, OBD is also mandated for some L-category vehicle classes, including an OBD step with strict emission thresholds. The technical implementation of this step is to be decided.

The regulation packages introduced in this period basically brought the emission control technology of L-category vehicles to the same level of development with the larger road vehicle types.

2.3.3. The future brings additional refinements

The Euro 5 stage introduced by Regulation (EU) No 168/2013 already sets very demanding targets for L-category vehicles with numerical emission limits which are at the same (or in some cases below the) level of passenger car ones. The same regulation has also introduced a package of additional safeguard measures. The exact technical implementation of these measures will be confirmed and further elaborated within an Environmental Study foreseen by the Regulation. This should underpin the technical implementation of the various measures. Issues which still need to be clarified include the extension of the SHED tests for evaporation control in more vehicle types, the final dates and levels of the Euro 5 limits, and the implementation and requirements of OBD. Additional issues concerned are the necessity of regulation of off-cycle emissions, the need for an introduction of a particle number limit, and the possibility to introduce an in-use conformity requirement. These developments are planned to cover regulatory requirements for L-category vehicles at least until




















L1e-A	L1e-B	L2e	L3e	L4e	L5e-A	L5e-B	L6e-A	L6e-B	L7e-A	L7e-B	L7e-C
											
											
											
≤50cc, ≤45 km/h, <4 kW, C-0 25kmh	≤50cc, ≤45 km/h, <4 kW	≤50cc, ≤45 km/h, <4 kW, ≤270 kg (P: V 0.6 m³)			3W, <1000 kg, max 5 seats	3W, <1000 kg, max 2 seats, V 0.6 m³	<4kW, ≤425 kg ≤45 km/h (D, G)	<6kW, ≤425 kg ≤45 km/h (D, G)	<15kW, ≤450 kg	W/G<6, ≤450 kg	P: ≤450 kg, U: ≤600 kg, (D, G)

Figure 2: Distinction of L-category vehicles to classes and types and characteristic vehicle examples

the Year 2025 time frame. It may also be expected that sooner or later CO₂ targets may be set for this category as well. This will increase the demand for more fuel efficient and /or alternative fuelled concepts.

2.4. Assessment of regulatory requirements and impacts on vehicle technology

Vehicle emission regulations become increasingly stringent for all road vehicle types, starting from small power two wheelers to large heavy duty trucks. This is the result of the continuous pressure to resolve air quality problems but also the need to reduce GHG emissions from transport.

In fact, reducing CO₂ emissions and the dependence on liquid fossil fuels appears as the main priority in road transport policy today. This decision has been expressed at a very high level within the European policy framework and it is clearly represented by solid targets set in the Transport White paper (COM/2011/0144 final) and the 2030 framework for climate and energy policies (COM(2014) 15 final).

The specific targets set have repercussions to the whole road transport sector, including infrastructure and planning changes, enhancement of logistics, increasing involvement of financial tools to reduce demand or to shift transport to particular directions, etc. It also brings though fundamental changes to the technology utilized in vehicles. Research and investment in combustion efficiency gains, improved and alternative fuels, hybrid and electric powertrains, and use of lightweight materials and enhanced aerodynamics are primarily promoted to reduce fuel consumption and GHGs. Several of these solutions may also bring benefits in terms of air pollutants, thus creating synergies between GHG and AP. It is expected that this trend will further intensify in the future as more research resources are brought in the area and technological maturity increases.

This trend is also boosted by the increased environmental awareness of the community and by the relative increase in the cost of conventional energy sources. Concepts that have earlier been turned down due to inferior performance (e.g. electric vehicles) or an underdeveloped refuelling network (e.g. LPG) today become popular because they offer monetary gains. Other concepts, such as hybrid vehicles, become popular because of their environmental performance despite the fact that customers need to pay a premium. This demonstrates that the societal choices change and become more receptive of new ideas provided they can demonstrate energy efficiency and air emission benefits over conventional solutions.

Such an environment of regulatory pressure and societal receptiveness creates a fertile ground for new vehicle technologies and concepts. Although it is not to be expected that such concepts will constitute the majority of vehicles sold in Europe in the near future, certainly a wider diversification with regard to powertrain technologies and fuels is to be anticipated. Vehicle sales statistics show that more than 30 hybrid vehicle models were available in Europe in 2013, although they make only some 1 % of total sales (ICCT, 2013). This is deemed to increase as more and more models are offered.

It has been mentioned that CO₂ reduction targets may become beneficial for air pollutants as well. The possibility for a wide introduction of electric vehicles will not only result in a higher efficiency in energy consumption but also zero exhaust pollutants at a local (urban)

level. The struggle for GHG benefits may sometimes though lead to opposite effects. This has been clear in the past with the shift in diesel cars that occurred in the 2000-2004 time frame. The 1999 voluntary agreement to reduce CO₂ emissions between the automotive industry and the European Commission (1999/125/EC) led the diesel market to explode from 20 % of total car sales in 1998 to 50 % by 2004 (ACEA, 2014). Although this had a marginal positive impact on CO₂ emissions, it significantly affected NO_x emissions at a European level (Borken-Kleefeld and Ntziachristos, 2012). Similar trade-offs are today encountered with a range of vehicle technologies, such as the increase in fuel consumption by the use of DPFs and lower NO_x limits, the increase in PM and HC with the implementation of gasoline direct injection vehicles, etc. Such trade-offs have not received appropriate attention from policy. Optimization (e.g. adopting a binned or a cap system to allow flexibility within a Euro stage) in such cases could potentially offer benefits in both CO₂ and air pollutants together with cost savings. It could also offer placement of particular alternative technologies under certain bins towards meeting an average target.

With regard to air pollutants, the issues remaining include diesel NO_x (and primary NO₂) and emissions of particulate matter from all vehicle types, including non-exhaust emissions (Borken-Kleefeld and Ntziachristos, 2012). Emissions at a Euro 6/VI level and Euro 5 level for L-category vehicles are designed to address these air quality issues, provided that the targeted reductions will be reached in the real world, over the lifetime of the vehicle. This is what enhanced regulations related to durability, in-use conformity, and OBD aim at. Any alternative technologies and concepts under consideration should also take lifetime performance into account. For example, a diesel hybrid vehicle with aged batteries may result to much higher emissions than when type-approved and a much higher relative increase than a conventional diesel vehicle of the same age. Similarly, vehicles operating on alternative fuels need to be tolerant to fuel specification variations so that unexpected emission levels or elevated levels of unregulated pollutant emissions do not occur.

In terms of the conventional vehicle and combustion concepts (diesel and petrol combustion), the low limits that have been proposed require complex and costly aftertreatment systems to be reached. Moreover, the inclusion of RDE in emission control means that aftertreatment systems need to be more robust and effective over a wider operating range than today's vehicles. OBD, although present in previous technologies, becomes now increasingly demanding. The OBD will need to demonstrate its diagnosis cycle over a much more transient driving cycle (WLTC), with reduced threshold limits and with enforced IUPRs. This means that OBD algorithms and sensors will have to be enhanced to adequately perform in the new environment.

Such developments will necessarily increase maintenance cost, the probability of failures, and the requirement of strict control of fuel specifications. Regulations in some cases are so strict for conventional vehicles, to the point where technological feasibility is not confirmed. Examples of such occasions include the low thresholds for OBD PM and the absence of suitable sensors, the extremely low limits for some L-category vehicles combined with a demanding driving cycle. The strict regulations and the increasing technical complexity and cost increase the competitiveness of alternative concepts that reach the limits with lower complexity. For example, electric L-category vehicles are expected to become popular, instead of conventional gasoline or diesel ones, partly owed to the strict emission limits expected for such vehicle types (Ntziachristos et al., 2013).

3. Technology Assessment Methodology

3.1. Vehicle types considered

The emission regulation and low limits for both air pollutants and greenhouse gases outlined in the previous chapter will be met by a range of vehicle technologies and fuel types. This creates the need to provide appropriate, or at least indicative, emission factors for all these concepts. All sizes of road vehicles were considered in this report; hence the first distinction has been made according to size, in the following main categories:

- Light duty vehicles (LDVs), comprising passenger cars (PCs) and light commercial vehicles (LCVs).
- Heavy duty vehicles (HDVs), comprising trucks and buses.
- L-category vehicles, comprising mopeds, motorcycles, tricycles and quadricycles.

No further split is done between PCs and LCVs. This is because the emission limits, the type approval procedure and the technology of the two vehicle types are similar. In reality, LCV emission factors will differ because of the different tuning and operation pattern of LCVs in real-world conditions, compared to passenger cars. However, the main levels and trends should be similar between the two vehicle types so the same aggregated emission factors may be used. The main two fuels used on this category are gasoline and diesel.

Heavy duty vehicles also comprise a wide range of vehicle types, from small mini-buses to long-haul trucks, reaching up to 60 t gross vehicle weight. So far, emission limits for these vehicles are assigned to the engine (in g/kWh) and not to the vehicle as such. Therefore, similar technological development occurs in engines of different sizes. This would mean that different emission factors, expressed in g/vkm, would be encountered in reality. In expressing the emission factors, we have selected a typical 42 t long-haul truck as representative of the truck category and a 15-18 t standard urban bus, as representative of the bus category. Scaling up or down of these emission factors would be necessary for different sized vehicles. The HDV category is dominated by diesel vehicles.

Finally, the L-category of vehicles is also a wide and diverse group. This earlier contained only mopeds and motorcycles. However, recent developments in the market and in the type approval procedure have introduced new vehicle types in this category, including three wheelers, quadricycles, all-terrain vehicles, small delivery vehicles, and micro-cars (see section 2.3.2). Gasoline has historically dominated the market. Today, gasoline vehicles continue to be the majority by far, but also diesel and electric vehicles – mostly in the micro-car type – contribute to the total sales. Therefore, gasoline and diesel vehicles are separately examined in this category.

3.2. Technology coverage

The report first provides aggregated emission factors for the vehicle technologies in compliance with the latest emission standard in time of writing. This corresponds to Euro 6 for passenger cars, Euro VI for trucks and buses, Euro 3 for L-category vehicles. Separate emission

factors are given for diesel and gasoline LDVs and L-category vehicles, due to the different emission limits and the distinct character of the emission performance of these vehicle types.

The studies available have shown that hybrid vehicles, further to the fuel consumption benefits they offer, they also lead to lower levels of conventional air pollutant emissions. For this reason, a separate set of emission factors is provided for gasoline-hybrid passenger cars. A discussion is also included with regard to diesel-hybrid cards, and the few vehicle models which are available in the European market.

Further to diesel and gasoline, some other fuels have also been significantly contributing in the total energy consumption of road transport. The two main ones have been natural gas (NG) and liquefied petroleum gas (LPG). Vehicles operating on any of these two fuels have to comply with either the diesel (HDV) or the gasoline (LDV) limits. However, use of a different fuel may lead to differentiation in the emission performance in some pollutants and under certain conditions. Moreover, vehicles operating on these two alternative fuels may have been originally designed by their manufacturers or they may have later in their lifetime been retrofitted to operate on the new fuel. A separate set of emission factors is proposed in these cases for originally designed and retrofitted vehicles.

In the HDV category, and in particular on buses, an intermediate step has been until recently offering the most stringent emission limits. This voluntary step, called Enhanced Environmentally friendly Vehicles (EEV) was introduced to allow the certification of urban vehicles that could offer additional environmental benefits, compared to the Euro standard applicable at that time. The EEV step was more stringent even than Euro V and has been the most stringent HDV limit until the introduction of Euro VI. In addition to conventional diesel technologies that made it into EEV, natural gas and biogas, ethanol fuelled, and even diesel-hybrid buses became popular in several European cities. Separate sets of emission factors are therefore given for the different EEV bus technologies.

Further to technologies already existing, an effort was made to provide emission factor estimates for some of the future technologies that have or are going to appear. Some of these technologies have already been foreseen with the emission standards designed for the future years, in particular Euro 6c for LDVs and Euro 4 and Euro 5 for L-category vehicles. Moreover, a discussion is added on the role of battery electric vehicles and fuel-cell vehicles and the role of next generation fuels, including second generation biofuels.

Table 6 provides the vehicle types and emission control technologies for which emission factors are provided in this report.

3.3. Pollutants coverage

The report provides aggregated emission factors for a range of pollutants. These can be split in the following groups:

- Regulated pollutants: Vehicle emission regulations enforce limits for Carbon Monoxide (CO), Total Hydrocarbons (THC), and Nitrogen Oxides (NO_x). Particulate Matter (PM) and Particle Number (PN) limits also exist for diesel and gasoline direct injection vehicles.

Table 6: Vehicle types and technology coverage in this report

Light Duty Vehicles	Heavy Duty Vehicles
Gasoline Euro 6 PFI	Diesel Euro VI
Gasoline Euro 6 GDI	EEV Bus w/o DPF
Diesel Euro 6	EEV Bus with DPF
Gasoline-Hybrid Euro 6	EEV Bus Stoichiometric CNG
Diesel-Hybrid Euro6	EEV Bus Lean Burn CNG
LPG OEM Euro 5	EEV Ethanol Bus
LPG Retrofitted Euro 5	
CNG OEM Euro 5	L-category vehicles
CNG Retrofitted Euro 5	Gasoline Euro 3
Gasoline Euro 6c	Diesel Euro 3
Diesel Euro 6c	Gasoline Euro 4/Euro 5
Battery Electric and Fuel Cell	Diesel Euro 4/Euro 5

Emission factors for these pollutants are proposed for all vehicle categories, fuels, and technologies in this report. In particular, PN corresponds to solid particles only, measured according to the PMP protocol. Vehicles are known of also producing volatile and semi-volatile particles, but there is no consistency in how measurements are done, hence no values are proposed for this extended list of particle species in the present report.

- Non-regulated pollutants: Ammonia (NH_3) is only regulated for HDVs that utilize ammonia-based NO_x aftertreatment control. However, NH_3 is primarily produced from catalyst equipped gasoline vehicles. Typical emission levels of NH_3 are hence proposed for all vehicle types in this report. Also, 'direct' or 'primary' NO_2 as a fraction of total NO_x is proposed. Primary NO_2 is directly emitted by vehicles and is not a product of atmospheric transformations. Direct NO_2 is of concern because of its toxic nature and because some vehicle aftertreatment systems promote its formation.
- Greenhouse gases: Emission factors are proposed for nitrous oxide (N_2O), a potent greenhouse gas. Its formation is promoted by several of the new vehicle aftertreatment technologies, in particular for diesel vehicles. A share of methane (CH_4) to THC is also proposed. Methane is not of particular importance as a greenhouse gas from road vehicles, due to its very low emission rate. Emission factors for CO_2 are not proposed as CO_2 is regulated on a fleet and not on a single vehicle basis. Moreover, this does not primarily depend on the aftertreatment or combustion technology but on vehicle size and separate vehicle measures that the manufacturer has introduced. Hence, typical average emission levels of CO_2 are not proposed.

No speciation of THC other than the split to methane and non-methane hydrocarbon is proposed. However, several of the technologies and fuels considered may have a significant impact on some of the components of THC and also on other organic species. Pollutants for

which particular concern exists include oxygenated compounds such as aldehydes and ketones, benzene, poly-aromatic hydrocarbons (PAHs), nitro-PAHs, and chlorinated compounds such as dioxins, furans, hexachlorobenzene, etc. A recent review of available information on chlorinated compounds has been conducted by Pastramas et al. (2014). However, more reliable information is required to identify the impact of individual combustion and aftertreatment technologies on such species.

Finally, metallic emission factors originating from the fuel, the lube oil and engine wear can be of importance due to their toxic nature. Metals such as mercury, chromium, and platinum group metals among others are known for their direct biological effects. COPERT 4 (Ntziachristos et al., 2009b) provides equivalent fuel contents in these metals, based on a review by Gkatzoflias et al. (2011) and Winther and Slentø (2010). As these emissions are not so much technology specific, the reader is directed to these studies for more information.

3.4. Main sources utilized

A number of sources have been utilized to develop the emission factors in this report. Key sources utilized are the following:

- **ERMES:** The European Research group on Mobile Emission Sources (ERMES) is an ad hoc group formed by the main research institutes in Europe who develop and maintain transport emission models. The group coordinates and follows the activities in models COPERT, HBEFA, and VERSIT+. The group maintains a database of vehicle emission tests conducted around Europe and, on the basis of this, develops emission factors that are used in the different models.
- **MVEG:** The European Commission has set up and maintains several working groups that develop the technical background for the vehicle emission regulations in Europe. The Motor Vehicle Emission Group (MVEG) has been traditionally the oldest group. Lately, this has become more specialised by maintaining groups with specific work programmes on motorcycle emissions, PEMS implementation, PM measurement, etc. Presentations and technical information delivered in these meetings is a very useful source of information.
- **GRPE:** The United Nations Economic Commission for Europe (UNECE) has historically been the first international organisation under which uniform emission limits were designed in Europe. UNECE maintains the Working Party on Pollution and Energy (GRPE), under the World Forum for Harmonization of Vehicle Regulations (WP.29), where common global regulations for vehicle emissions are sought for. Specific works under the Particle Measurement Programme (PMP) and the Gaseous Fuelled Vehicles (GFV) programme have provided several insights into future regulation and technology development.
- **IEA-AMF:** The International Agency Association (IEA) has set up and Advanced Motor Fuels Implementing Agreement (AMF) which aims at better understanding the fuel effects on vehicles technology and their emission performance. The Agreement is brought in place by the means of work concentrated around specific Annexes. The institutes involved in the activities of IEA-AMF have produced many useful reports, related to fuel/vehicle interactions.

- DG-JRC: research work being conducted at the Directorate General Joint Research Centre (DG-JRC) of the European Commission delivers up-to-date information on vehicle emissions, using new techniques and methods, which are applied in preparation of the upcoming Regulations. Particularly important in this area are related studies on non-regulated pollutant characterisation, real-world vehicle emission characterisation using PEMS, and work on moped and motorcycle emissions.
- Research Projects: Research projects funded by the European Commission have been over the years trying to deliver emission factors for road vehicles. Historic programmes have been FP4 MEET, FP5 ARTEMIS and FP5 PARTICULATES and, currently, FP7 TRANSPHORM. Information from these projects has been consulted, where necessary.
- Industry and private projects: Several associations and nongovernmental organizations have sponsored and coordinated research projects on the production and collection of information related to vehicle emissions. Particular active in this area has been the Association for Emissions Control by Catalyst (AECC), the oil companies' European association for environment, health and safety in refining and distribution (CONCAWE), and the International Council on Clean Transportation (ICCT).

Further to these key studies and sources, a large number of individual research works and studies available in the technical and scientific literature were accessed to collect information on emission performance of late technology vehicle types.

3.5. Emission factor development

Developing precise emission factors for vehicles is a tedious task. This is primarily because the operation of road vehicles is variable and because they can operate in many different conditions. Unlike most of the other anthropogenic sources, vehicle emission rates may differ by orders of magnitude at each second of operation, depending on whether the vehicle accelerates, slows down, or tries to keep a constant speed. Moreover, environmental conditions that the vehicles operate at may have a profound effect on the emission levels of some pollutants. For example, engine start at cold winter conditions in Northern Europe may lead to orders of magnitude difference in the CO and PM emission levels of a gasoline vehicle, than starting the same vehicle on a hot afternoon in the south. Precise emission factors also need to take into account the impacts of fuels and ageing on emissions. Improper fuel use, normal ageing of emission control systems, and the increase in the probability of malfunctions with age are all factors that have an impact on average emission levels from a fleet of vehicles.

The task becomes increasingly difficult as the complexity of emission control system increases in late technology vehicles. In particular with regard to diesel technology, a typical heavy-duty Euro VI exhaust line may often consist of five separate aftertreatment components (oxidation catalyst, diesel particle filter, urea hydrolysis catalyst, selective catalytic reduction, and ammonia slip catalyst) with variable degree of performance of each of them, depending on the operation conditions. To add to the complexity, late technology vehicles complying with the same emission standard, may often exhibit different emission control technology packages. For example, gasoline direct injection vehicles may either operate on

stoichiometric or lean-burn combustion, therefore producing different profile of pollutants and necessitating different emission control technologies to decrease emissions. The configuration of the emission control determines to a very large extent the operation of the vehicle in real world operation.

Emission factors derived for regulated pollutants can at least be compared to emission limits to obtain confidence over the order-of-magnitude levels. One will of-course need to explain differences, if large deviations between emission factors and emission limits are established. Such differences are often dramatic. A typical example is real-world NO_x over emission limits for diesel LDCs. However, the uncertainty in providing emission factors for non-regulated pollutants can be even larger as no reference to provide an order of magnitude level exists. Moreover, the different emission control systems utilized may lead to order of magnitude differences in the emission levels of non-regulated pollutants, as these are not pollutants that are specifically targeted by each aftertreatment system. Therefore, vehicles fulfilling the same emission standard may substantially differ in their non-regulated pollutants level.

Providing precise emission factors would therefore necessitate extended measurement campaigns of vehicles within the same emission standard stage but of different technology, fuel, and age, operating under various driving and environmental conditions. Ideally, several vehicles of each type should be measured to obtain reliable emission factors related to the mean level and the uncertainty range. Unfortunately, such measurement campaigns are costly. Fully characterising emissions of a vehicle is in the order of several thousands of Euros (equipment investment costs, labour, consumables, renting and hire costs ...) and measuring all the combinations needed would make the whole exercise a multimillion project. In the absence of appropriate resources emission factors need often to be developed on the basis of a handful of tests or, at worse, no tests at all. The latter is particularly true for forecasting emission factors of future vehicle technologies.

The intention with the emission factors presented in this report is that they should reflect average emission levels of complete fleets of vehicles, driven over normal driving schedules. Such emission factors need to encompass, to the degree possible, the impact of all factors discussed above, that is operational and environmental conditions, ageing, fuel effects, etc. For several of the technologies examined, no such information is available. In these cases engineering judgement has been used to estimate proposed emission levels. Because of the complicated nature of this exercise and the limited information available, a qualitative rather than a quantitative approach has been used. With this, emission factors are proposed for three distinct driving conditions, as shown in Table 7.

The main steps involved in the process of developing the three emission factor modes are summarized in the following steps

- Base emission factors for regulated pollutants have been collected from trusted sources (section 3.4) on a separate file. Information on the background of such emission factors is also collected.
- The impact of cold start is estimated and appropriately quantified for the urban mode when the base emission factor does not include the impact of cold-start. Cold excess emission over starts, based on the work of Alvarez et al. (2009); Andre and Jourmard

Table 7: Relevance of emission factors proposed in this study

Mode	Typical mean speed range (km/h)	Description
Urban	15-30	Encompasses effects of typical city driving with frequent stops, cold start effects, and most of diurnal and soak evaporation emissions. City driving is considered to occur in urbanized areas with road speed limit of 50 km/h.
Rural	50-70	Relaxed free-flow driving in secondary roads outside of the city with a speed limit in the 70-80 km/h range. Occasional slow-downs to cross urbanized areas and infrequent stops.
Highway	85-110	Corresponds to typical driving at motorways with a speed limit of 110-130 km/h. Mostly constant speed driving with speed adjustment to the traffic and infrequent stops (e.g. for tolls).

(2005) and Weilenmann et al. (2013) are assessed and the basic COPERT 4 cold start approach is modified appropriately. Then, this is applied to the base emission factor.

- The impact of ageing has been addressed by consideration of the durability factors proposed in the methodology. These are considered to reflect typical ageing effects on emission control systems over the lifetime of the vehicles. As any durability factor is considered to reflect deterioration over the complete vehicle lifetime, half of this deterioration is considered for typical fleet vehicles.
- Fuel evaporation is in addition considered for gasoline vehicles, based on factors calculated with COPERT 4 for typical environmental conditions and fuel properties in Europe.
- Research and scientific studies have been collected on emissions of non-regulated pollutants. In general, average values collected from these studies have been used as typical emission levels. Several times, emission levels ranged substantially in the literature. Technology and engineering assessment was utilized in these cases to select appropriate emission levels. The selection criteria have been case-specific.
- Technological proximity has been utilized where no information on emission levels exists. Typical cases include alternative fuels and non-regulated pollutants. Diesel or gasoline equivalencies, depending on the combustion principle, have been used in these cases.
- Engineering assessment has been involved to estimate emission factors for future vehicle types. The main assumptions in each such assessment are outlined on a per case basis.

The emission factors proposed are not primarily meant to replace those already used in national inventories, emission models, or research studies. However, they can be used when no other information exists or to confirm the levels of the already used emission factors. When large differences with the proposed emission factors are found, one may need to identify and confirm the reasons for this.

3.6. Organic compounds and CH₄ emission factors

Methane is a key greenhouse gas with limited air quality impacts. This is why volatile organic compounds (VOCs) in the exhaust need to be separated into their methane (CH₄) and nonmethane (NMVOC) part. Current regulations in US have shifted from the regulation of NMVOC to the regulation of nonmethane organic gas (NMOG), which include oxygenated compounds like aldehydes and ketones, produced by the addition of oxygenated molecules (basically ethanol in gasoline). Therefore, the complete group of methane, nonmethane hydrocarbons and oxygenated species is called Total Organic Gas (TOG).

However, in the laboratory, measuring of organic species is conducted using a flame ionization detector (FID) that detects carbon atoms and is calibrated to respond to the molecular mass of propane. The FID reading corresponds to the Total Hydrocarbon Emissions (THC) of the exhaust. If the profile of organic species were known in the exhaust, then the THC reading would be equal to VOC. However, since this is not known a priori, THC will slightly differ to VOC by approximately up to 5 % (USEPA, 2005), depending on the vehicle technology and fuel. On the other hand, THC is always lower than TOG because FID does not respond to the carbon atoms linked to oxygen.

In this study, based on the approximate nature of the emission factors proposed, THC and VOC are considered to be identical, for simplification. Also, no information is given on TOG. The readers interested to convert from one species group to the other can successfully apply the approximations proposed in US (USEPA, 2005).

Methane emissions are low from today's cars, given the already low levels of tailpipe hydrocarbon emissions. Heeb et al. (2003) established levels of CH₄/THC in the order of 5 % for Euro 3 vehicles. A more recent analysis of experimental information by Katsis et al. (2012), based on the work of the Biogasmax project (Bach et al., 2010) found ratios ranging from 0 % to 33 % for late technology gasoline vehicles. A range up to 25 % was found for recent gasoline vehicles in US as well (May et al., 2014). As a result, a typical range of CH₄ emission factors for late technology (Euro 5 and Euro 6) gasoline vehicles is in the order of 3-8 mg/km, including cold-start. Because of their much higher hydrocarbon emissions, motorcycle CH₄ emission factors may be much higher, in the order of 10-100 mg/km, including the impact of cold start (Costagliola et al., 2014).

Diesel combustion has been traditionally leading to very low emission levels of CH₄. Recent experimental tests collected from diesel buses from Nylund and Koponen (2012) exhibit undetectable emission levels of CH₄ (<1 mg/km) in hot conditions. Diesel car CH₄ emission characterisation in Europe is very limited and practically nonexistent for late technology vehicles. In Asia, using local diesel fuel and diesel technology, methane emission factors for diesel cars, including cold start, have been measured in the range of 14-15 mg/km (Chiang et al., 2012; Tsai et al., 2012). US emissions factors used in greenhouse gas inventories are at much lower levels, close to 0.3 mg CH₄/km (USEPA, 2014). In COPERT, a value of 1.1 mg/km is proposed for urban conditions and zero methane emissions for urban and rural conditions. A value of 1 mg/km is proposed as a CH₄ emission factor for late technology diesel vehicles (trucks and cars) in this report.

The vehicle types for which methane emission factor can be possibly important are vehicles operating on natural gas or biogas, which consist by more than 90 % of methane. Historic

emissions of up to 7.5 g/km have been measured (Hajbabaei et al., 2013) from CNG buses. Stoichiometric late technology EEV buses have been shown to emit below 300 mg/km (Nylund and Koponen, 2012) but emission levels up to 3.5 g/km have still been measured (Wang et al., 2014). COPERT EEV CNG bus emission factor is at 1 g/km which seems a representative average emission level, given the wide range of literature values.

Regarding recent technology CNG cars, the review of the BIOGASMAX project (Bach et al., 2010) by Katsis et al. (2012) provides emission levels from 27-57 mg/km, including the impact of cold-start. This basically means that more than 90 % of THC emissions from CNG cars correspond to CH₄, especially over cold-start conditions. Assuming 40 % share of the cold-start emission factor in total emissions (where applicable), Table 9 shows typical CH₄ emission factors for late technology vehicles of different types.

Table 8: Proposed CH₄ emission factors for late technology vehicles

Vehicle type	CH ₄ emission factor (g/vkm)
Gasoline mopeds and motorcycles	0.050
Gasoline LDVs	0.005
Diesel vehicles (cars and trucks)	0.001
CNG Flex-fuel cars*	0.035
CNG EEV Buses	1.0

* Split of this to Urban, Rural and Highway modes is provided in Table 19.

4. New Vehicle Technologies

4.1. Gasoline Euro 6 LDVs

4.1.1. Description

Gasoline, or petrol, engines have traditionally been the most popular propulsion systems for light duty vehicles. This is due to the high power to weight ratio of these engines, their smooth operation, and the possibility to build them in different sizes and configurations, practically from a few Watts (e.g. 500 W) up to several kWatts (e.g. 500 kW).

There are two main combustion concepts of such engines, with distinct characteristics. The most widespread one is the so-called port-fuel injection (PFI) engine, where the fuel is injected in the intake manifold, upstream of the combustion chamber. This allows time for the fuel to evaporate and mix with the intake air and hence creates an almost homogenous (premixed) mixture that forms relatively limited pollutants upon combustion. The second concept is the gasoline direct injection (GDI) one, where the fuel is injected directly in the cylinder. This allows precise metering of the fuel injected per stroke and cylinder, and better adjustment of the combustion parameters, such as compression ratio and valve and injection timings. This also leads to decreased pumping losses. As a result, fuel efficiency improves. The drawback is that the fuel is not thoroughly mixed with the intake air. Liquid fuel may impinge on the cold walls of the piston and the combustion chamber thus leading to higher emissions, in particular of PM and HC.

For their emission control PFI engines are calibrated stoichiometrically, which means that the quantity of fuel injected is precisely proportional to the air intake. This is combined with a three way catalyst (TWC) in the exhaust which oxidizes CO and HC and reduces NO_x. The technology has been proven very efficient over the years and may lead to a pollutant reduction that exceeds 99 %. Recent developments with regard to catalyst formulation, substrate optimization, and positioning of the catalytic converter in relation to the engine outlet have extended the performance and the useful lifetime of such systems (Johnson, 2013). Such a configuration may achieve the lowest emission levels of all conventional vehicle technologies today.

GDIs can be tuned both for stoichiometric and lean combustion, with the latter offering even higher efficiency improvements because the working medium is air during intake and for most of compression. Because of oxygen availability in the exhaust this concept is prone to high NO_x emissions. Stoichiometric engines on the other side perform for the most part similar to PFI. Because of their distinct performance, these two technologies need to be considered separately.

At a Euro 6 level, stoichiometric GDI engines can meet the emission limits with a TWC, similar to their PFI counterparts. However, the high engine-out NO_x emissions of lean burn engines means that some kind of NO_x aftertreatment is required to address them. The only commercial lean-burn GDI concept available in Europe today uses a NO_x adsorber to reduce NO_x (Kemmler et al., 2008). This operates by adsorbing NO_x over the lean phase on the catalyst surface and by reducing upon release over short cycles of rich operation (Brandt et al., 2002).

Most of the analysis in the following chapters is based on passenger cars. Light commercial vehicle regulations and aftertreatment technology follow the developments in the passenger car sector. For simplicity, in this report we assume same emission performance between LCVs and PCs. In reality, emission factors would be slightly differentiated basically because of the different operation patterns of LCVs compared to PCs. However, this difference should not be substantial to necessitate a completely new emission factor dataset.

4.1.2. Emission performance

Regulated Pollutants

Euro 6 emission limits did not differ numerically than earlier Euro 5 standards. Hence, the basic technology between Euro 5 and Euro 6 vehicles is the same. Because of the relatively good emission performance of gasoline cars already from a Euro 4 level, and their compliance with emission limits, emissions from Euro 6 cars have not received much attention. There have been a few campaigns on Euro 6 but the emphasis is on diesel NO_x, which indeed still remains a problem.

The only two regulated pollutants of concern for gasoline cars have been PM and, primarily, PN emissions from GDI cars, that have been shown to exceed those of corresponding diesel cars. Two other pollutants which have received little attention despite their potential environmental impacts are NH₃ and N₂O. Ammonia in particular has been observed in large quantities in some gasoline vehicles. These unregulated components are addressed in the following section.

With regard to regulated pollutants, HBEFA 3.2 offers up-to-date emission factors based on Euro 5 values and the consideration that the share of GDIs in the total fleet will increase from 35 % at a Euro 5 level to 58 % at the Euro 6 level, as a response to more demanding fuel efficiency targets (Rexeis et al., 2013). The hot emission factors proposed in HBEFA 3.2 for regulated pollutants have been adopted in COPERT 4 as well. Typical hot emission levels for urban, rural and highway conditions, according to HBEFA 3.2 are shown in Table 9.

Table 9: Hot exhaust emission levels of Euro 6 gasoline passenger cars (source: HBEFA 3.2)

Driving Mode	CO g/vkm	HC g/vkm	NO g/vkm	PM g/vkm	PN (×10 ¹¹) #/vkm
Urban	0.34	0.010	0.044	0.0023	18
Rural	0.55	0.010	0.020	0.0020	15
Highway	0.90	0.014	0.011	0.0024	19

Actual emission levels that should be used in inventories differ from these values due to a variety of reasons:

- The influence of cold-start significantly changes the average emission levels, in particular of CO and HC. The actual impact of cold starts depends on the ambient temperature, the frequency of starts per day, the trip distance distribution and others. For example, each start from an engine at a temperature of 22 °C adds 3 g CO and 1 g HC to emis-

sions of Euro 5 gasoline cars (Weilenmann et al., 2013). This has to be appropriately added to average hot emission levels, depending on the km driver per start. Traditionally, the cold start effect is added to urban driving because most of the trips start within the urban environment.

- The exact driving pattern under a certain driving mode also has an influence on emissions. In late vehicle technologies this becomes less important than speed, due to the strict stoichiometric control of recent vehicle technologies. A typical example on NO_x from gasoline cars is shown in Figure 3.
- The emission factors in Table 9 correspond to relatively new vehicles. Average emission levels for the complete fleet will be actually higher due to normal degradation of the emission control system and the disproportional contribution from malfunctioning vehicles.
- Hydrocarbon emissions should also take into account the impact of fuel evaporation, which becomes increasingly important as exhaust emission limits drop.

The influence of all these parameters can be taken into account using one of the available vehicle emission models. However, the available measured vehicle sample in Europe is very limited to precisely develop all the parameterizations required. Hence, despite continuous efforts to improve the emission modelling, the limiting factor has always been the relatively small dataset of vehicles available. For example, in the largest and more coordinated action in Europe to develop road transport emission factors (HBEFA), no petrol Euro 6 cars have actually been measured and the emission factors are only based on sound engineering assessments (Rexeis et al., 2013). It is expected that the emission factors for these newest vehicle technologies will improve in the future when more tested vehicles become available.

As has been explained in the previous section, conventional PFI gasoline vehicles have not been in the focus of dedicated studies, due to their good performance and emission limit compliance. However, the environmental performance of GDI cars and their technology vari-

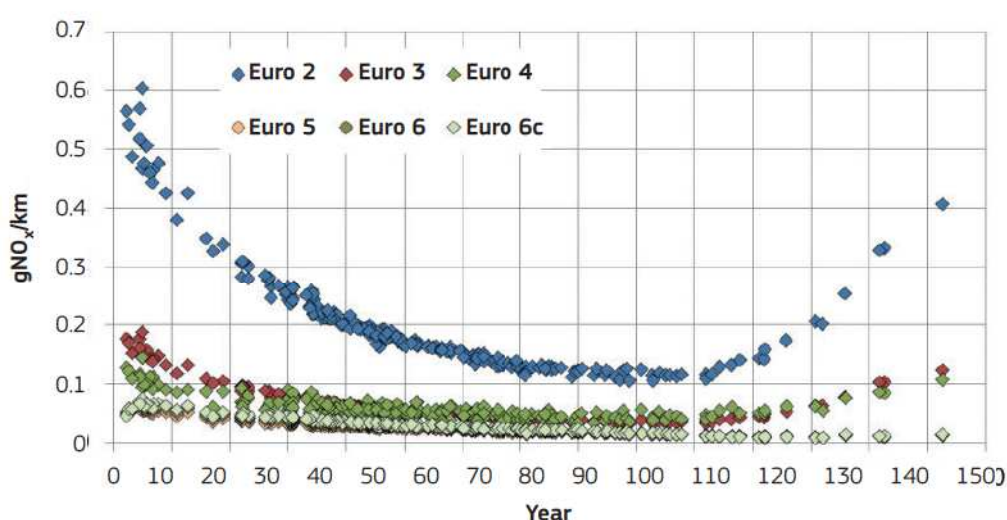


Figure 3: Impact speed and driving situations on NO_x emissions from gasoline cars (Rexeis et al., 2013)

ance has received some attention. In an effort to reveal how different GDI vehicle technologies affect emissions, five Euro 5 GDI cars were measured by AECC over a cold start NEDC and the complete suite of the Common Artemis Driving Cycles (CADC) (May et al., 2013). One of those vehicles was a lean GDI with NO_x storage aftertreatment and the other four vehicles have been stoichiometric GDI ones. All vehicles were found to produce HC well below the limit, with hot start levels being almost no detectable. CO emissions were also found much below the limit with the exception of one small vehicle overloaded at the high speed part of the CADC. NO_x and PM were also found below the limit in both cycles with the exception of the lean GDI vehicle that by far exceeded the limits over the CADC test.

This study confirmed that there are remaining issues with some Euro 5 GDI concepts. In particular, the lean and highly efficient GDI concept seems to reach distinctly high NO_x emissions over the CADC (almost 500 mg/km, compared to 20 mg/km for the stoichiometric GDI vehicles). At a Euro 5 level, only one manufacturer commercially implements this technology. It is not yet known how popular this technology will continue to be at Euro 6 level. Given its unique character, its performance over real-world at Euro 6 will have to be monitored.

The same study also confirmed that late technology Euro 5 GDIs emit significant solid particle numbers, which on average are at $\sim 13 \times 10^{11} \text{ km}^{-1}$. This level is not expected to significantly change at a Euro 6 level.

Finally, Table 10 presents the emission levels from the FP7 Transphorm project. The emission factors corresponding to France have been taken as an average for the continental Europe. Moreover, the GDI PN levels have been taken from the Euro 5 vehicles, as Transphorm does not distinguish between Euro 6 and Euro 6c. The distinct character of PFI and GDI vehicles is shown when one compares PM and PN emissions from these two concepts.

Table 10: Total exhaust emission levels of Euro 6 gasoline passenger cars (source: FP7 Transphorm)

Combustion Concept	Driving mode	CO	HC	NO _x	PM10	PN ($\times 10^{11}$)
		g/vkm	g/vkm	g/vkm	g/vkm	#/vkm
PFI	Urban	0.086	-	0.034	0.0005	3.6
	Rural	0.12	-	0.022	0.0005	3.1
	Highway	0.18	-	0.016	0.0012	1.3
GDI	Urban	0.086	-	0.034	0.001	49
	Rural	0.12	-	0.022	0.001	27
	Highway	0.18	-	0.016	0.0025	18

Unregulated Pollutants

Unregulated pollutants from gasoline Euro 6 vehicles have received limited attention in Europe. However, emissions of NH₃ and N₂O may be significant and could be largely underestimated in current inventories. Nitrogen dioxide (NO₂) does not seem to constitute a large problem, first because of the overall low NO_x emissions from most late technology gasoline cars, and because the combination of stoichiometric combustion and TWC has been known of not being favourable for NO₂ formation.

Recently, Pastramas et al. (2014) made a review of studies in order to develop NH_3 , NO_2 , and N_2O emission factors from late vehicle technologies. The review identified that the formation and the relative importance of these three species in the exhaust of vehicles depend on chemical processes that take part over the three way catalyst. The exhaust gas engine out composition, micro-deviations of stoichiometry to either lean or rich, the exhaust gas temperature, the catalyst formulation, and the catalyst ageing are all determining factors for the extent of formation of these species (Rahman et al., 2011). In general, partial reduction of NO can lead to either N_2O (preferred over lean environment) or NH_3 (preferred over rich environment) formation. After their formation, these two species also take part in reactions that destruct and form each other. Given the dynamic character of these processes, developing precise emission factors is impossible without a large vehicle sample and an extended measurement programme.

Regarding late technology NH_3 emissions, tests from only three Euro 5 gasoline car results were located in the literature (Bielaczyk et al., 2012; Suarez-Bertoa et al., 2013). Some of these exhibit very high NH_3 emissions – at the same or higher level than NO_x and much higher than the levels for diesel Euro VI trucks, for which ammonia is injected in the tailpipe and a specific limit exists. Results from equivalent technology vehicles in US confirm the European findings (Pastramas et al., 2014). Therefore, this is a potential environmental problem that has been left totally uncontrolled. Carslaw and Rhys-Tyler (2013) performed a series of remote sensing measurements in the UK and distinguished individual measurements according to vehicle type and emission standard level. Despite the known uncertainties of remote sensing measurement, which are associated with the momentary snapshot-like characterization of emissions and the measurement technique as such, the finding of this study provides some clear trends with regard to vehicle technology impacts on NH_3 emissions. In particular, it shows that NH_3 emissions at Euro 5 are at about 70 % of total NO_x emission levels.

Emission measurements of N_2O from late technology European gasoline vehicles could not be located in the literature. Pastramas et al. (2014) developed emission factors for COPERT 4 on the basis of technological equivalency with US specification vehicles, and mostly on the basis of a comprehensive study aimed at supporting US N_2O regulations (Ball et al., 2013). The emission levels established were at the 3 mg/km level and lower. However, levels even above 30 mg/km have been measured in the study of Rahman et al. (2011) for GDI vehicles. Moreover, the study of Ball et al. (2013) confirmed the impact of catalyst ageing on increased N_2O emissions, a trend which has been observed for earlier gasoline cars and has been included in COPERT 4. As explained, understanding of the detailed chemistry between NH_3 and N_2O is necessary to predict the relative significance of the two species in the exhaust. In US, GHG emission targets have also set light duty vehicle emission limits at 10 mg N_2O /mi. Similar standards should be developed in Europe as well to properly account for all GHG pollutants in the tailpipe. Such a development would also initiate measurement campaigns to develop precise emission factors.

As explained before, the relative importance of NO_2 on NO_x emissions from TWC equipped passenger cars is limited. Studies based on laboratory experiments come to NO_2/NO_x mass-based ratios in the order of 2-5 %. In their remote-sensing study, Carslaw and Rhys-Tyler (2013) observed a ratio of about 8 %. Given the low total NO_x emissions, and the low ratio

of NO₂ in NO_x, gasoline cars do not seem to constitute a significant contributor to direct NO₂ in urban areas.

4.1.3. Proposed emission factors

No actual measurements of Euro 6 gasoline cars could be found in the literature. However, given the identical emission limits with Euro 5 cars and the compliance of Euro 5 cars with limits, Euro 6 emission factors can be safely developed on the basis of the Euro 5 measurements.

The proposed emission factors should take into account, to the extent possible, the hot emission levels, the impact of cold start, the impact of fuel evaporation, and the impact of ageing.

Reliable hot emission levels for regulated pollutants can be taken from the latest version of HBEFA 3.2 (Rexeis et al., 2013). Weilenmann et al. (2013) also presented cold start over emission for Euro 5 gasoline cars, expressed as g/start, for various temperatures. These cannot be used directly because they only refer to a particular driving cycle, starting from ambient temperature. However, these are used to scale the COPERT cold start emission factors, which have been based on Euro 4 cars (Andre and Joumard, 2005). Cold-start over emission is then added to the urban emission factor. The base emission factor derived with this process, is then scaled upwards by half of the deterioration factor included in the regulations for each pollutant (CO: 1.25, HC: 1.15, NO_x: 1.3, PM: 1.0), to account for the impact of age on emissions. Finally, the impact of evaporation on emissions is added based on the methodology of COPERT 4, using European average fuel and climatic conditions and a split of 80:10:10 distribution of evaporation to urban, rural, and highway conditions, respectively. The emission factors developed with these considerations are provided in Table 11.

Unregulated gaseous emission factors are derived from the study of Pastramas et al. (2014). The NO₂/NO_x ratio proposed (5 %) is at the high end of the experimental results collected from the various vehicle tests sources. Actually, the remote sensing data of Carslaw and Rhys-Tyler (2013) provide an even higher ratio of 8 % in ambient conditions. Since all the other emission factors were based on dynamometer studies, we have retained the value of 5 % with consistency to the measurement conditions of the other pollutants.

The emission factors for particulate pollutants from GDI vehicles originate from the study of May et al. (2013) that have been differentiated for urban, rural and highway driving, according to the relative trends of the FP7 Transphorm project. The PFI levels come directly from the FP7 Transphorm database. All these are shown in Table 12.

Table 11: Emission factors (g/vkm) of gaseous pollutants proposed for Euro 6 gasoline cars

Driving Mode	CO	HC	NO _x	N ₂ O	NH ₃	NO ₂ /NO _x (wt.)
Urban	0.91	0.19	0.081	0.0025	0.007	0.05
Rural	0.69	0.014	0.025	0.0002	0.008	0.05
Highway	1.13	0.019	0.015	0.0010	0.022	0.05

Table 12: Emission factors of particulate pollutants proposed for Euro 6 gasoline cars

Driving Mode	PFI		GDI	
	PM10 g/vkm	PN ($\times 10^{11}$) #/vkm	PM10 g/vkm	PN ($\times 10^{11}$) #/vkm
Urban	0.0005	3.6	0.0010	20
Rural	0.0005	3.1	0.0010	11
Highway	0.0012	1.3	0.0025	7.5

4.2. Diesel Euro 6 LDVs

4.2.1. Description

The regulation of diesel cars at a Euro 6 level has received more public attention than probably any other previous emission standard step, as a result of the unacceptably high NO_x emissions of Euro 5 cars (Fontaras et al., 2014; Weiss et al., 2011b) and the consequences they have had in meeting the air quality targets in Europe (Borken-Kleefeld and Ntziachristos, 2012).

As a result, a number of emission control technologies have been proposed to meet the stringent emission limits. In terms of engine measures, a typical Euro 5/Euro 6 diesel engine utilizes high-pressure multi-pulse common rail injection, multi-valve cylinder heads, and exhaust gas recirculation (EGR). The approach for aftertreatment NO_x control diversifies for different manufacturers. One existing commercial implementation of Euro 6 is materialized with no deNO_x aftertreatment, but the control of NO_x is realized with engine measures only (Terazawa et al., 2011). A second strategy utilizes a lean NO_x trap (LNT) to meet Euro 6 limits. For example, Volvo and BMW among others, have adopted this approach for their early Euro 6 vehicles (Bickerstaffe, 2009; Laurell et al., 2013). Other manufacturers have followed the SCR principle for controlling NO_x emissions (Neusser et al., 2013), with ammonia injection in the exhaust line.

The situation becomes even more complex, as manufacturers prepare for the following step (Euro 6c). Therefore, different concepts, combining a number of these techniques (e.g. LNT+SCR or lean NO_x catalysts +SCR) may already start to appear (Johnson, 2014) at various degrees in the period from 2014 to 2017.

The variety of emission control concepts utilized means that the prediction of representative levels of real-world NO_x emissions becomes difficult. Although it is expected that all systems would be similarly effective over the regulatory driving conditions, their performance over a wider operation window will not depend so much on the baseline technology, but on its exact calibration. The main issue is that high deNO_x efficiency means higher fuel consumption and, in the case of SCR, higher consumption of urea additive. As a result, manufacturers would on one hand try to optimize the system to achieve regulatory NO_x requirements and, on the other, to moderate fuel consumption increase (De Cesare et al., 2014). In the case of Euro 5 cars, this balance leaned mostly to the side of fuel consumption benefits over real-world conditions, which led to the unacceptably high NO_x emissions. An additional concern is

the sensitivity of some systems, in particular SCR, to temperature. In the past, applications of SCR to refuse trucks that operated at low exhaust gas temperature demonstrated a relative inefficiency in NO_x emission control (Vermeulen et al., 2012). High temperature in the exhaust gas also means low efficiency and the effort generally is to avoid this. Moreover, urban driving does not generate so much heat that risks SCR efficiency. Improvements in the SCR catalysts and implementation may solve these issues.

An additional concern is the cost and complexity of the different systems. In particular SCR systems have been considered to add a significant cost burden to small diesel vehicles, to the point that their price difference over their gasoline counterparts makes them financially not competitive. Therefore, alternative applications with no deNO_x aftertreatment or with passive NO_x control systems may appear for smaller vehicles that would limit active deNO_x systems (SCR, LNT) to the larger car segments only. For example, BMW utilizes LNT for their 2.0 l diesel engines and SCR for their 3.0 l ones to meet Euro 6b levels. Therefore, depending on the market structure in each country, diesel Euro 6 levels may also differ because of the variability in the proportion of different NO_x control concepts on the actual fleet.

Euro 6 cars also utilize a DPF to control PM and PN within regulatory limits. The basic concept is similar to Euro 5 with a proven high efficiency and reliability. Euro 6, as a natural development, utilizes systems of improved performance and better packaging. DPFs, in contrast to NO_x emission control techniques, constitute a total filter in the exhaust line and are considered to effectively reduce emissions under any operation condition. The only departure from this rule is the DPF condition during regeneration, i.e. during the periodical burn out of soot that accumulates in the DPF so that a new loading cycle begins. Such regeneration events occur every few hundreds of kilometres, last for a few minutes and increase the particle concentrations as soot is combusted in the filter. The increase in the particle concentration over normal levels can be from one to three orders of magnitude, depending on the DPF configuration (Mamakos and Martini, 2011). However, just because the regeneration operation lasts for only a fraction of normal operation (~0.5 % of total time), the contribution of regeneration to total emissions is moderate. Rexeis et al. (2013) estimated emissions during regeneration periods to increase PM and PN levels by 42 %.

4.2.2. Emission performance

Regulated Pollutants

The two most comprehensive studies of Euro 6 diesel emission performance have been produced within the ERMES group by TUG (Rexeis et al., 2013) and TNO (Ligterink et al., 2013), in a rather collaborative manner. The TNO report also makes reference and compares own results with three other studies in Europe performed by AECC (May et al., 2013) in Belgium (actual tests conducted in Germany), the Institute of Transport Economics (Hagman and Amundsen, 2013) in Norway (tests conducted in Finland), by ADAC (Gauss, 2011) in Germany, and also PEMS results conducted by DG JRC (Weiss et al., 2012).

These studies collected a sample of more than 25 either Euro 6 or prototype Euro 6 diesel vehicles, covering all technologies for NO_x control (EGR only, EGR+SCR, EGR+LNT). The prototype vehicles were either demonstrator vehicles from the corresponding manufacturers or vehicles mainly sold in the US market.

The HBEFA 3.2 emission factors proposed for urban, rural and highway driving are shown in Table 13, while the NO_x emission factors proposed for the Dutch air quality studies are shown in Table 14. HBEFA emission factors are based on simulations over typical driving cycles on averaged vehicle types. By using engineering assumptions, the Dutch emission factors also take into account the probability that each of the technologies may fail to deliver the promised reductions in real world conditions. Despite the different samples used and the different approach, the two sets of emission factors are consistent to each other.

Table 13: Hot exhaust emission levels of Euro 6 diesel passenger cars (source: HBEFA 3.2)

Driving Mode	CO g/vkm	HC g/vkm	NO _x g/vkm	PM10 g/vkm	PN (×10 ¹¹) #/vkm
Urban	0.056	0.039	0.27	0.0025	9.4
Rural	0.056	0.038	0.27	0.0014	3.7
Highway	0.066	0.028	0.41	0.0013	2.6

Table 14: NO_x emissions factors for Euro 6 diesel passenger cars proposed in the Dutch inventory (source: Ligterink et al. (2013))

Driving Mode	NO _x g/vkm
Urban	0.24
Rural	0.20
Highway	0.43

The main conclusions from these studies can be summarized in the following points:

- Despite the relatively satisfactory size of the vehicle sample collected, the uncertainty for the diesel NO_x emission factors remains high. This is the result of the diversification in emission control technologies but also because the vehicle sample collected consists both from prototype and high-end vehicles which may not be representative of the actual structure of the Euro 6 fleet that will be deployed in the different countries. The concern is that the actual fleet will also consist of vehicles of lower specs with higher NO_x emission levels in real world conditions than the values measured for the high-end vehicles.
- A dynamic situation for average Euro 6 emission levels is expected over the years. The short period (3 years) between Euro 6 and Euro 6c means that several manufacturers will start making vehicles available to the market that comply with Euro 6c earlier than 2017. In the same period, other manufacturers may offer vehicles which are basically retuned Euro 5 concepts, instead of real Euro 6, in anticipation to Euro 6c. Real-world NO_x emissions from such different vehicle technologies can differ by more than one order of magnitude. Examples of such diversities were also observed between the vehicles collected in the sample tested.
- No evidence exists for the impact of ageing on emissions and only limited information is available on the impact of low temperature on NO_x emissions. Given that the NO_x emission control systems utilized are highly optimized and calibrated to provide emission

reductions over the statutory driving cycle only, the concern is that such conditions will lead to a substantial increase in the emission levels.

- Emissions of all other pollutants seem to be well controlled at a Euro 6 level with CO levels traditionally much lower than those of petrol cars and hydrocarbon levels that do not seem to constitute a real environmental problem. Most importantly, PM and PN emissions seem well controlled, similar to the Euro 5 evidence.

As a recommendation, all studies suggest that Euro 6 emission levels have to be constantly monitored with new tests in the lab and on the road in order to warrant that emission reductions are taking place, as new vehicle models appear in the market. Potential failure of Euro 6 LDVs to deliver real world NO_x reductions will result to persistent air quality problems and legal and monetary implications for the member states (Borken-Kleefeld and Ntziachristos, 2012).

Unregulated Pollutants

In contrast to petrol cars, the lean environment in diesel exhaust means that all species that can be further oxidized (e.g. NH_3 , N_2O) should be satisfactorily decreased in the oxidative environment of the exhaust line. However, the implementation of deNO_x catalysts at Euro 6 level has complicated this general rule. The intentional injection of NH_3 on SCR systems may be a reason for ammonia emissions when the system is overdosed (ammonia slip). No provisions on ammonia slip control for Euro 6 cars have been made in the regulations yet (as is the case with HDVs), hence this could prove a potential environmental problem. Moreover, the SCR systems may form N_2O in conditions when ammonia is only partly oxidized, especially at low SCR operation temperatures (Kamasamudram et al., 2012). Therefore, SCR systems may lead to a change in the perception that diesels are overall low emitters of N_2O and NH_3 .

The oxidative environment in the exhaust line also promotes the conversion of NO_x to NO_2 , which may result to yet another increase in the NO_2/NO_x ratio. SCR operation ideally requires equal NO_2 and NO concentrations (Grossale et al., 2009) for successful operation, in particular in the typical temperature range of diesel exhaust ($<250^\circ\text{C}$). Hence high NO_2/NO_x ratios should be satisfactorily dealt upon by the SCR. Moreover, NO_2 can be consumed for the oxidation of soot within the DPF. Of course, this is only possible when the DPF follows the SCR, as is the case in some HDV applications. In most of the passenger car applications expected though, the SCR positioning is preferably downstream of the DPF (Tourlonias and Koltsakis, 2011), therefore any of the NO_2 escaping the SCR will not be consumed by the soot. Finally, systems that utilize an ammonia slip catalyst as the last element of their after-treatment system may also lead to high NO_2/NO_x ratios in the tailpipe, depending on the selectivity of catalyst to NH_3 conversion. The exact aftertreatment implementation will determine NO_2/NO_x ratios, which may therefore substantially vary from vehicle to vehicle.

The HBEFA (Rexeis et al., 2013) and TNO (Ligterink et al., 2013) studies propose NO_2/NO_x ratios which are in the order of 30-40% for Euro 6 cars. This is at the same or slightly above the level for Euro 5 cars. As explained above, this will largely depend on the relative presence and the performance of the various emission control options in the fleet.

With regard to NH_3 and N_2O emissions, the review by Pastramas et al. (2014) revealed the complete lack of Euro 6 measurements for NH_3 and N_2O emissions in the literature. Emission factors for these two pollutants were therefore derived based on technological equivalence with US concepts. Still, this is an area that has to be more thoroughly studied given the potential importance of these two pollutants in air quality and climate change, respectively.

4.2.3. Proposed emission factors

Based on the previous analysis and the studies collected, the emission factors proposed for diesel passenger cars at a Euro 6 level are provided in Table 15 and in Table 16 for gaseous and particulate pollutants respectively.

Hot emission levels of regulated pollutants originate from HBEFA 3.2. Cold start is known to have a small impact on diesel emissions. In the absence of latest information on the cold-start emission performance of Euro 5/6 diesel cars, the COPERT 4 cold-start impact has been added on the HBEFA 3.2 emission levels. Finally, similar to Euro 6 gasoline cars, a correction for NO_x and HC emissions has been conducted, assuming 50 % of the deterioration considered in the regulations. The levels of CO and PM are considered not to deteriorate with time.

Table 15: Emission factors (g/vkm) of gaseous pollutants proposed for Euro 6 diesel cars

Driving Mode	CO	HC	NO_x	N_2O	NH_3	NO_2/NO_x (wt.)
Urban	0.085	0.050	0.30	0.010	0.007	0.30
Rural	0.055	0.040	0.28	0.004	0.007	0.30
Highway	0.066	0.029	0.43	0.004	0.007	0.30

The N_2O emissions from diesel cars need to be taken well into account in the calculation of total GHG emissions of light duty vehicles. Considering the CO_2 equivalent of N_2O (298), the 10 mg/km level corresponds to 3 g/km extra CO_2 equivalent emissions, or some 5 % of total GHG of the most efficient Euro 5/6 diesel cars in the market today. This has to be considered in designing the next GHG targets at a European level. The US regulations have already introduced an N_2O limit of 10 mg/mile (~6 mg/km) for light duty vehicles, based on concerns specifically raised for late technology diesel vehicles (USEPA, 2010).

Table 16: Emission factors of particulate pollutants proposed for Euro 6 diesel cars

Driving Mode	PM10 g/vkm	PN ($\times 10^{11}$) #/vkm
Urban	0.0027	9.3
Rural	0.0015	3.7
Highway	0.0014	2.6

4.3. Hybrid LDVs

4.3.1. Description

In hybrid cars the power is provided by two alternative powertrain systems. Most commonly, a reciprocating internal combustion engine is combined with an electric motor to power the vehicle. The two powertrain systems may be arranged in different configurations, depending on the architecture and the engineering targets set. The most popular hybrid systems today are the ones utilizing the “power-split” approach, where power to the traction wheels can be provided independently or combined by both the motor and the engine. The most representative vehicle of this architecture is the Toyota Prius. Series hybrid configurations have also appeared where the engine is used to power a generator that charges a battery, which in turn powers the electric motor to the wheels. The series hybrid vehicle is more often characterised as an electric with range extender. Opel Ampera is a commercial implementation of this concept.

The term plug-in hybrid is used to characterise those vehicles that can be directly charged from the electric grid. The plug-in capability is not associated with the powertrain configuration. A power-split hybrid or a series hybrid may or may not be plug-in. The Volvo V60 is a good example of a plug-in hybrid where none of the two (power-split or series) concepts has been implemented. Rather, a diesel engine powers the front axle and an electric motor powers the rear axle. This is sometimes referred to as an “axle-split” hybrid (Agliany et al., 2012). Finally, hybrids may be distinguished to “strong” and “mild”. In mild hybrids, the electric motor is relatively small and is not able alone to power the vehicle. It only kicks in to assist the engine over transients. The Honda Civic is a characteristic commercial example of a mild hybrid. More details on hybrid architectures may be found in technical handbooks. Ntziachristos and Dilara (2012) provide a summary of the sustainability and performance of the key architectures.

Hybrid vehicles are primarily produced to control energy consumption and production of greenhouse gas emissions. This is achieved by trying to decouple power production from power consumption needs. The objective is that the engine should operate, to the degree possible, at its highest efficiency mode. If this results to power surplus, then the extra energy is used to charge the batteries. If there is a deficiency in power, then the motor kicks in to fill in the power surge. With such a mechanism, the engine remains shut at creeping flow or stop-and-go conditions that would otherwise result into high entropy production. Several of the hybrid vehicles, and certainly the plug-in hybrid ones, also offer an electric-only mode, during which the vehicle is only powered by its motor. This electric mode can last from a few to several decades of kilometres, hence enough for everyday commuting before recharge. Plug-in vehicles produce no exhaust pollutants in such an electric-only mode.

4.3.2. Emission performance

Regulated Pollutants

Because of the operation of the engine at optimum, air pollutant emissions may also be reduced in hybrid vehicles. Furthermore, operation of the vehicle in the electric-only mode may result to zero emissions in real-world conditions. Overall, despite the fact that gasoline

hybrid vehicles are type approved according to the Euro standard enforced at time of their launch, they emit lower than their conventional counterparts in real terms. A particular problem that has to be addressed is that the intermittent engine operation is a challenge for the aftertreatment systems that need to sustain a certain temperature level for efficient operation. Special thermal management is hence required (Koltsakis et al., 2011). In fact, Alvarez and Weilenmann (2012) demonstrated that the cold-start behaviour of commercial hybrid vehicles is better than that of gasoline vehicles due to more freedom in engine management. In particular, higher than necessary load at the beginning may be used to enable a fast engine and catalyst warm up, with the excess power delivered to the batteries. This initially results to higher fuel consumption than conventional vehicles, which is later cancelled out by the efficient engine operation when warmed up.

COPERT 4 provides speed-dependent emission factors for hybrid gasoline vehicles, based on the work of Fontaras et al. (2008). These originate from tests on a chassis dyno from two of the most widespread hybrid vehicles in Europe at Euro 4 level. These vehicles already at that time were much below the Euro 6 standards, emitting conventional pollutants close to the detection limit. Further work by DG JRC using PEMS (Martini et al., 2010) confirmed the low emission levels by measuring two gasoline hybrid vehicles over real-world conditions. Work in US (Johnson et al., 2014), also using PEMS, has provided speed – specific power binned emissions of different hybrid vehicles that will be used for emission modelling in the framework of the MOVES model. They also confirmed that emissions of hybrid vehicles remained low for a wide range of the engine map and only increased at the extreme high power, high speed operation points, which are not frequent in real-world operation.

A recurrent issue with some gasoline hybrid vehicles is the unexpectedly high particle number emissions as a result of the spiky emissions during engine start-up (Robinson and Holmen, 2011; Wei and Porter, 2011). The average emission levels measured with the hybrid vehicles tested are comparable with current technology GDI vehicles, and exceed the particle number limits to be enforced in Europe by 2017. Presumably, momentary enrichment of the engine, high speed cranking residual gases, or retarded ignition to guarantee a smooth start-up are reasons for this spiky behaviour (Zhou and Yuan, 2011). This phenomenon requires monitoring and remedial measures if it proves to hold true for several hybrid vehicle models. Latest (unpublished) measurements by the Laboratory of Applied Thermodynamics in the framework of the ERMES activities on a 2013 model Toyota Auris HSD and a 2012 model Prius Plug-In hybrid vehicle did not confirm these findings, with mean PN levels at 5×10^{11} km⁻¹, including the power demanding ERMES and the new WLTC driving cycles. Therefore, a somehow higher PN than conventional vehicles is confirmed but not to a level that should constitute a real compliance problem.

It was not possible to locate any literature data on the emission performance of diesel hybrid vehicles. This is because commercial diesel-hybrid vehicles only appeared in mass production in 2013. Only simulation studies have been performed so far, that generally demonstrate the potential of diesel hybrids for emission reduction over conventional diesel cars, as expected (Gao et al., 2012; Millo et al., 2009). Real world data from diesel hybrid buses that are shown in the next section do not confirm such reductions over conventional

diesel buses. However, the use and tuning of a series hybrid bus is potentially different to a diesel hybrid passenger car so conclusions are not directly transferrable.

Whether diesel hybrids will perform better than conventional Euro 6 cars remains to be seen. The technology utilized indeed offers the potential to decrease NO_x by engine optimization and by delegating transient operation to the electric motor. At the same time, low NO_x would naturally lead to higher fuel consumption, thus undermining the benefits of hybridisation. A possible scenario is that diesel-hybrid manufacturers will try to achieve Euro 6 without SCR, only by EGR optimization. This is for two reasons, first to control the already high costs of a diesel hybrid powertrain and, second, because the intermittent engine operation may not provide enough heat to sustain high SCR efficiency. EGR optimization is known to perform well within the limits of the regulation but leads to uncontrolled NO_x emissions when it is not used. It is therefore the tuning of the whole system, rather than the technology itself that may or may not lead to substantial real-world NO_x emission reductions.

At this stage, that no RDE is in place, we propose that Euro 5/6 emission factors of hybrid vehicles should be kept at the same levels as with their conventional diesel counterparts. This is based on the known principles of NO_x/CO_2 trade-offs. Since currently the emphasis is disproportionally in favour of CO_2 reductions, it is expected that current diesel-hybrid configurations will also be tuned to serve low CO_2 targets. Future configurations, in compliance with the Euro 6c targets may also offer overall better NO_x performance, again similarly to their conventional diesel counterparts.

Unregulated Pollutants

The study of Carslaw and Rhys-Tyler (2013) provides trends of NO_2/NO_x ratios and NH_3/NO_x ratios for hybrid petrol cars, in comparison with conventional cars. The results at a Euro 4 level show that the NO_2/NO_x ratio for hybrid vehicles is higher than conventional petrol cars and that absolute ammonia levels at Euro 4 are actually higher than (the very low measured) NO_x levels. Euro 5 NH_3 hybrid levels are similar to conventional cars but the ratio of NO_2/NO_x reaches 15 %. These results show a distinct character of unregulated pollutants for hybrid vehicles, however starting from very low levels of NO_x . Given the uncertainties related to the RSD measurement and the low levels of NO_x from hybrid vehicles, we have opted on retaining the same levels of unregulated pollutants with conventional petrol vehicles. More efforts to devise hybrid specific emission factors for those pollutants are however highly advised.

4.3.3. Proposed emission factors

The emission factors proposed for Euro 6 gasoline hybrid cars are shown in Table 17 for gaseous pollutants and in Table 18 for particulate pollutants. The hot emission factors for regulated gaseous pollutants originate from COPERT 4 hybrid functions, assuming typical environmental and driving conditions. Cold-start excess has been added to the urban emission factor, taking into account the work of Alvarez and Weilenmann (2012), and by appropriately scaling the Euro 6 conventional gasoline car excess emission. Durability correction has been conducted similar to conventional gasoline Euro 6 cars.

Gaseous unregulated pollutant levels have been kept at the same level as conventional Euro 6 gasoline cars. It should be noted that Carslaw and Rhys-Tyler (2013) have observed higher NO_2/NO_x and NH_3/NO_x ratios for Euro 5 gasoline hybrid vehicles than conventional ones, using remote sensing measurements. This will have to be explored with laboratory tests as well.

Particle mass and number emissions are based on averaged levels of unpublished data conducted by LAT in the framework of ERMES, and the work of Robinson and Holmen (2011) and Wei and Porter (2011).

It should be repeated that for diesel hybrid cars at Euro 6 levels, the same emission factors with conventional diesel Euro 6 cars are proposed.

Table 17: Proposed emission factors (g/vkm) of gaseous pollutants for gasoline hybrid Euro 6 cars

Driving Mode	CO	HC	NO_x	N_2O	NH_3	NO_2/NO_x (wt.)
Urban	0.63	0.18	0.012	0.0025	0.007	0.05
Rural	0.035	0.004	0.001	0.0002	0.008	0.05
Highway	0.019	0.004	0.023	0.001	0.022	0.05

Table 18: Proposed emission factors of particulate pollutants for gasoline hybrid Euro 6 cars

Driving Mode	PM10 g/vkm	PN ($\times 10^{11}$) #/vkm
Urban	0.001	7.2
Rural	0.001	5.0
Highway	0.001	11

4.4. Alternative fuelled LDVs

4.4.1. Description

There are two main alternative fossil fuels used in transport, that is liquefied petroleum gas (LPG) and natural gas (NG), either in compressed (CNG) or liquid (LNG) form. Natural gas is often used as a feedstock for the production of other fuels, such as dimethyl ether (DME) and methanol (MtOH).

LPG is a by-product of the separation of raw natural gas or a by-product of oil distillation for the production of gasoline and diesel. It mainly consists of two light components of petroleum, propane and butane. LPG has historically been flared in refineries due to its low commercial value. It is a gas in ambient conditions. It becomes liquid when compressed at moderate pressure of 5-10 bars. It is stored in pressurised tanks on board the vehicle in liquid form to benefit from the increased volumetric energy content compared to its gaseous form. Its exact properties depend on the proportion of propane and butane as well as other hydro-

carbons in its mass. In general, it has approx. 80 % of the energy content of gasoline per litre and an octane number (RON) in the range of 105-110 (this increases with the propane/butane ratio). More information on the specifications of LPG used in transport can be found in EN589 standard.

LPG may be combusted in a normal gasoline type of engine that has to be adjusted to the specifications of the fuel. In particular, injection duration needs to increase to counterbalance the lower specific energy content compared to gasoline while ignition timing needs to be advanced to account for the slower burning speed of LPG. Most importantly, the air to fuel ratio needs to be adjusted to maintain stoichiometry of combustion. With proper tuning, LPG engine operation is hard to distinguish from gasoline.

OEM realisations of LPG cars mostly refer to bi-fuelled vehicles, i.e. cars that can operate both on gasoline and on LPG. This is to increase the range of the vehicle and for security, if LPG refuelling stations cannot be found in a particular area. Converting a gasoline engine to LPG is so easy that can be made in any local car repair shop. Due to the ease of conversion and the lower cost of LPG at the pump, many petrol vehicles have been converted to LPG around the world, using commercially available retrofit kits. Traditionally large LPG fleets in Europe are present in Poland, the Netherlands and Italy, and lately Greece. Outside of Europe, LPG cars constitute a large fraction of Korean and Australian fleets.

The other alternative transport fuel is natural gas (NG). NG is often mixed up with LPG but it is an entirely different fuel. It consists primarily of methane and ethane, therefore it is lighter than LPG and more difficult to store. Natural gas can be stored either compressed at pressures over 200 bar (CNG) or cryogenically in liquid form at temperatures approximately -162 °C (LNG). Despite the extreme conditions, the volumetric energy content of NG still remains from 5 times (CNG) to 1.8 times (LNG) less than gasoline. This creates limitations on carrying sufficient quantity of fuel on board the vehicles. This is why natural gas derivatives are sought for, such as DME, MtOH or other Gas-To-Liquid (GTL) fuels. These liquid derivatives of NG offer a much higher volumetric energy content and ease of handling for refuelling and storage. Actually, MtOH is one of the first alternative fossil fuels used in transport already since the 1970s.

Despite the energy content disadvantage, NG is considered as a promising fuel for the future. Its advantages include its widespread availability and alternative energy pathway to oil – that promotes energy security – its low CO₂ yield per unit of energy delivered, and the ability to directly substitute it with biomethane, i.e. the product of biomass conversion. For these reasons, the automotive industry currently gives strong emphasis on the development of natural gas passenger cars to benefit from the availability of NG and its 20-25 % lower CO₂ yield than conventional gasoline.

In cars, natural gas is burned in conventional stoichiometric gasoline-type of engines. The specific characteristics of natural gas make conversion of current gasoline vehicles much more difficult than conversions for LPG. Due to the high pressure of storage and handling, CNG installations have better to be done by the OEMs. Retrofitted vehicles have also appeared but not at the extent of LPG retrofits.

NG can be also used as a diesel substitute in larger vehicles, either in lean combustion or in compression ignition engines with diesel in pilot injection and NG during the main injection (dual fuel engines). Implementation of natural gas in such cases is examined in section 4.6, which refers to EEV buses.

4.4.2. Emission performance

Regulated Pollutants

Properly adjusted stoichiometric LPG and NG vehicles should little differ in terms of their regulated components emissions, compared to gasoline ones. This is because all three fuels generally contain same families of species (paraffinic hydrocarbons –gasoline also contains aromatics) and because spark ignition combustion proceeds in the same way between the fuels. Only CH₄ from NG vehicles is substantially higher than gasoline, as the fuel as such is 90 % methane and this is relatively difficult to combust in cold spots within the combustion chamber.

Most importantly, once stoichiometry has been established, the TWC in the exhaust line should lead to a very efficient reduction of CO, HC and NO_x. Due to the low reactivity of CH₄ from CNG engines, a dedicated TWC would be required for sufficient reduction of the methane part of HC (Bach et al., 2010). A study by Vonk et al. (2010) in the Netherlands showed that OEM LPG and CNG cars were hardly distinguishable from gasoline cars of the same standard (Euro 4) in terms of NO_x emissions. The same study also presented that the retrofitted LPG and CNG cars emitted much above the limits on average. Some of the retrofitted cars emitted up to four times more NO_x than the mean level of the diesel Euro 4 cars examined in that study. The same has also been observed in the measurements on a race track conducted with PEMS on different vehicles, included OEM and retrofitted LPG and CNG cars (Martini et al., 2010). While the OEM CNG cars performed indistinguishably from petrol cars, two retrofitted CNG and LPG cars exhibited NO_x levels (>1 g/km) which are even higher than diesel cars.

One particular problem has been that retrofits are verified for their safety and operation but no emission test is required to confirm that the vehicle continues to comply with the emission limits after the conversion. The only emission test that the vehicle will need to pass is the short inspection test, which only addresses CO and HC at low and high idle. This may lead to uncontrollably high NO_x emissions. Bach et al. (2010) explained that the different air-to-fuel ratio required for alternative fuels than gasoline as well as cross-sensitivities of the lambda sensor, require recalibration of the ECU of the vehicle for retaining a precise stoichiometry. Czerwinski et al. (2010) confirmed that due to such cross-sensitivities, the lambda sensor shifts CNG combustion to the rich side with reduced NO conversion and increased ammonia production. Martini et al. (2010) considered that lean, rather rich operation, is responsible for the high NO_x emissions observed. Whatever the cause (rich or lean combustion), even slight deviations from stoichiometry - which are inevitable in retrofit systems - are deemed to result to very high NO_x emissions.

By measuring 13 CNG cars at a Euro 4 level and comparing to gasoline operation, Bach et al. (2010) came to the conclusion that a distinct character of OEM CNG cars compared to gasoline is only visible on their CH₄/THC ratio which is dominated by CH₄. Therefore, higher

THC and CH₄ levels were established for CNG over real world conditions, than gasoline. When Euro 6 OEM CNG cars appear, it is expected that they will fully comply with applicable limits, without particular problems.

With regard to PN and PM emissions, Aakko and Nylund (2003) and Ristovski et al. (2004) identified no particular differentiation between gasoline and alternative fuelled OEM vehicles. In case of slightly rich operation, that could be the result of a retrofit though, particle number and mass emissions may also be increased. Furthermore, in the case of LPG, the delivery method may have an impact on emissions. Lee et al. (2010) observed significant differences in the particle numbers in the exhaust of LPG vehicles equipped with different fuel delivery systems.

Finally, it should also be stated that, compared to gasoline cars, CNG and LPG vehicles do not suffer from evaporation emissions, due to the high-pressure sealed tanks used in both cases.

Unregulated Pollutants

There are two main unregulated pollutants of concern for spark-ignition alternative fuelled vehicles. The first is methane emissions from CNG cars and the second is NH₃ emissions from both LPG and CNG. Neither N₂O nor NO₂ are particularly significant pollutants from spark-ignition engines and we do not expect that a change in the fuel would have a significant impact on the emissions of any of those two species.

The studies outlined above on regulated pollutants have all identified that CNG cars emit approximately the same quantity of HC with gasoline cars. However, more than half of total HC emissions in CNG cars consist of methane. This is important to account for in the calculation of climate impacts of the use of NG, but it does not constitute a significant air quality concern. Moreover, engine and aftertreatment measures to reduce emission of CH₄ can be implemented. Therefore, it is not known whether relatively high emissions of CH₄ will be a problem in OEM Euro 6 cars.

Ammonia emissions from Euro 4 and Euro 5 cars have been measured by Bach et al. (2010) and Bielaczyk et al. (2012). Euro 5 OEM cars have been shown to emit ammonia at equal or below gasoline levels when fuelled either by LPG or CNG. However, Euro 4 cars have been shown to emit much above gasoline levels. No study could be located where NH₃ emissions from retrofitted cars were measured.

4.4.3. Proposed emission factors

Gasoline based emission factors have been the basis for the emission factors proposed in this report for alternative fuelled vehicles. PN and PM levels are considered identical to gasoline PFI levels. LPG use in DI engines (no such concept known today) would most probably also result to GDI level of PN emissions.

With regard to gaseous pollutants, the following differences over gasoline cars have been considered:

1. No evaporation of LPG takes place, hence LPG HC emission factors are lower than gasoline cars.

2. Total CNG HC emissions are higher than gasoline cars, due to the contribution of methane on total emissions. Emission factors are taken from COPERT 4, which are based on the work of Bach et al. (2010).
3. Methane fraction of HC for CNG cars is at much higher level than gasoline and LPG.
4. Two levels of NO_x are given, one for OEM and one for retrofitted cars; the latter based on consistent evidence from Martini et al. (2010) and Vonk et al. (2010) that shows much higher levels than OEM cars. The average ratios between CNG/Gasoline and LPG/Gasoline from Vonk et al. (2010) have been used to derive proper NO_x emission factors from retrofitted vehicles.

Table 19: Proposed emission factors (g/vkm) of gaseous pollutants for alternative fuelled vehicles

Driving Mode	CO	HC	NO _x	N ₂ O	NH ₃	NO ₂ /NO _x (wt.)
Urban	0.85	LPG: 0.12 CNG: 0.13 of which 55 % is CH ₄	OEM: 0.072 Retrofitted CNG: 0.25 Retrofitted LPG: 0.17	0.0025	0.007	0.05
Rural	0.61	LPG: 0.013 CNG: 0.05 of which 55 % is CH ₄	OEM: 0.028 Retrofitted CNG: 0.10 Retrofitted LPG: 0.067	0.0002	0.008	0.05
Highway	1.04	LPG: 0.017 CNG: 0.070 of which 65 % is CH ₄	OEM: 0.014 Retrofitted CNG: 0.050 Retrofitted LPG: 0.034	0.001	0.022	0.05

4.5. Diesel Euro VI HDV

4.5.1. Description

The regulation of emissions at a Euro VI level is even more demanding than the control of LD vehicles. This is because fuel efficiency for commercial long haul vehicles is of paramount importance. Hence, compromises in fuel efficiency to accommodate emission control targets are not well received by the HDV operators. Furthermore and in contrast to LD, HD emissions are controlled over the complete engine map and in-use compliance (in other words 'real drive emissions') provisions are already in place, corresponding to a more holistic regulatory environment than LD.

In the past, both in US and in Europe, the anticipation of an emission stage that was considered to increase fuel consumption accelerated sales of earlier technology vehicles. Such a pre-buy was evident in US in 2006, in anticipation of the US2007 emission stage. Therefore,

every new HDV technology stage needs to warranty that the consumption does not increase and, even better, decreases over the previous stage. Current evidence in Europe suggests that real fuel consumption up to the Euro V level has been continuously dropping, despite increasing stringency in emission control (Schuckert and Krukenberg, 2011).

The trend is expected to continue at a Euro VI level as well, also taking into account the upcoming regulations on CO₂ labelling for trucks. The main concerns for fuel consumption increase in HDVs have been the need of a DPF to reduce PM and PN emissions in the exhaust line and the very low NO_x levels that may lead to degraded combustion in order to meet them. Both concerns seem alleviated as current evidence on Euro VI trucks suggests that efficient SCR systems and combustion efficiency improvements more than counterbalance the negative impact of DPF and low NO_x limits on fuel consumption.

The basic configuration of a Euro VI engine and aftertreatment devices is rather similar among the different manufacturers. Euro VI engines benefit from high combustion efficiency due to improved turbocharging operation compared to previous generations, increased fuel injection pressure and matched injection strategy, optimisation in the combustion chamber geometry, compression ratio adjusted for best compromises between optimum efficiency and low soot production rate, and others (Kruger et al., 2012). Therefore, Euro VI engines are thermodynamically more efficient than Euro V ones, a development that contributes to better fuel efficiency.

A typical exhaust line of a Euro VI truck consists of a series of aftertreatment components (Gense et al., 2006). The first component is a DOC that increases the production of NO₂ and the temperature of the exhaust gas before this enters a catalysed DPF which collects soot. Urea injection takes place downstream of the DPF and is hydrolysed before it enters the main SCR catalyst where NO_x levels are reduced. The final component is an ammonia slip catalyst that oxidises any excess ammonia to avoid ammonia slipping above the regulatory limit of 10 ppm. According to the regulations, this complex system needs to deliver sufficient reductions over 700000 km of operation for trucks of more than 16 t gross vehicle weight.

Although this basic configuration is rather an industry standard, the individual details and the calibration of the engines may differ significantly between manufacturers or even between different vehicles series of the same manufacturer. One path is to significantly increase combustion efficiency and NO_x emissions and then install a very efficient SCR to get rid of the high engine-out NO_x emissions. One such commercial system (IVECO) does not even use EGR to reduce engine-out NO_x. Other implementations follow a more conservative approach that sacrifices some of the engine efficiency to control engine-out NO_x emissions by EGR (cooled or not cooled) and precise turbocharging adjustment (often with variable geometry) to come up with lower engine-out NO_x emissions. Presumably, such an approach would result to lower urea consumption by SCR than the first alternative.

The DPF control strategy may also differ in the different commercial applications. In contrast to passenger cars where active regeneration by post-injection of a specific fuel quantity is materialized, heavy duty applications try to mostly benefit from passive DPF regeneration. This is made possible due to the overall higher load and the resulting high temperature of HDV exhaust. Also, the higher power-specific NO_x and NO₂ emissions than passenger cars

enable effective low temperature oxidation of soot in the DPF. Passive regeneration contributes to lower fuel consumption as post injection is not necessary in this case. For safety reasons, driver induced regeneration by dashboard activation is offered in some cases (SCANIA).

Major upcoming developments in the area that can be expected as Euro VI matures, include improved efficiency by means of excess heat recuperation (Aneja et al., 2011). This will significantly change the engine/aftertreatment configuration and calibration. For example, combustion efficiency may be intentionally degraded so that engine-out NO_x are decreased while the overall efficiency improves by utilising the excess heat in the recuperation system. In terms of aftertreatment changes, combined DPF+SCR systems may offer synergies for NO_x /soot suppression while overall decreasing the volume required and offering better packaging options (Johnson, 2014). Finally, the OBD PM thresholds may also lead to further optimizations of the whole system.

4.5.2. Emission performance

Regulated Pollutants

Emission measurements of Euro VI trucks have been performed by a number of institutes in Europe. VTT have performed a large number of tests in their full size chassis dynamometer (Laurikko et al., 2014). TNO studied the relative reductions of Euro VI over Euro V, utilizing PEMS. Finally, HBEFA 3.2 has lately delivered a comprehensive dataset of emission factors for Euro VI trucks (Rexeis et al., 2013).

All individual sources demonstrate an exceptional consistency in that Euro VI vehicles achieve impressive reductions in both NO_x and PM levels over Euro V trucks. This includes cold-start performance and also emission levels over non-regulatory cycles. Table 20 shows emissions factors for 42 t Euro VI trucks operating on a level ground with 50% of their maximum payload from two studies. The two datasets present some differences, i.e. the HBEFA seems to be based on a sample rather tuned towards higher NO_x / lower PM emissions, while the VTT averages are the other way round. Despite these differences, the levels presented in Table 20 need to be compared with Euro V NO_x and PM levels, of 3 g/km and 0.03 g/km, respectively. Therefore, small differences between the two datasets at Euro VI level are not significant.

Table 20: Comparison of typical emission factors for 42 t trucks between HBEFA 3.2 and a VTT study (Laurikko et al., 2014; Rexeis et al., 2013)

Driving Mode	NO_x (g/vkm)		PM (g/vkm)	
	HBEFA	VTT	HBEFA	VTT
Rural	0.32	0.24	0.007	0.013
Highway	0.28	0.21	0.004	0.011

Unregulated Pollutants

Similar to passenger cars, the operation of the SCR may lead to a dynamic chemistry between NO, N₂O, NH₃, and NO₂ in the exhaust line of Euro VI trucks. But, in contrast to passenger cars, the ammonia slip regulatory limit of 10 ppm creates a safety margin for truck emissions, with regard to NH₃.

There are a very limited number of non-regulated pollutant measurements for late technology diesel heavy duty trucks in Europe (Czerwinski et al., 2009; Hagman and Amundsen, 2013; Willner, 2013). Pastramas et al. (2014) compiled these individual measurements and collected information from US and Japan tests on similar technology vehicles, on which emission factors on non-regulated pollutants were built. These are presented in the next section.

4.5.3. Proposed emission factors

Two emission factor sets are presented, one corresponding to typical long haul truck of 42 t operating on level ground with 50 % of its maximum payload and one set for typical non-articulated buses. NO_x and PM levels originate from the work of Laurikko et al. (2014), who provide such aggregated emissions factors, while CO, HC and PN originate from HBEFA 3.2. Non regulated pollutants originate from the study of Pastramas et al. (2014).

Table 21: Emission factors (g/vkm) of gaseous pollutants proposed for Euro VI trucks and buses

Driving Mode	CO	HC*	NO _x	N ₂ O	NH ₃	NO ₂ /NO _x (wt.)
42t Articulated truck						
Road	0.30	0.02	0.24	0.019	0.009	0.30
Highway	0.10	0.01	0.21	0.019	0.009	0.30
15t Standard Bus						
Urban	0.52	0.03	0.85	0.015	0.009	0.30
Rural	0.13	0.02	0.22	0.015	0.009	0.30
Highway	0.17	0.01	0.21	0.015	0.009	0.30

* Very low measured levels, values quoted are estimates only

Table 22: Emission factors of particulate pollutants proposed for Euro VI trucks and buses

Driving Mode	PM10 g/vkm	PN (×1011) #/vkm
42 t Articulated truck		
Road	0.013	1.5
Highway	0.011	1.0
15 t Standard Bus		
Urban	0.009	1.2
Rural	0.003	0.4
Highway	0.003	0.5

4.6. EEV Buses

4.6.1. Description

Already in 1999, Directive 1999/96/EC introduced a voluntary stage of low emission limits, the so called EEV – Enhanced Environmentally friendly Vehicles. This stage was already more strict in all pollutants than the Euro V limit that was introduced almost ten years later, except for NO_x , where the two emissions steps were at the same level. Before Euro VI arrival, EEVs represented the lowest emission level for HDVs. With the mandatory arrival of Euro VI since 2014, EEV becomes rather obsolete.

The EEV step mostly aimed at urban buses and coaches. It represented an effort by the policy makers to achieve two main objectives: firstly, to stimulate technological development towards low emissions and secondly to deliver an emission stage that could consistently be used by local authorities to introduce clean vehicles where air quality problems mounted. Because of the strict limits at that time and its voluntary character, the EEV stage was not met by one technology only but by a variety of concepts offered by the different manufacturers. Directive 2009/33/EC attempted to provide some further guidance and criteria on the ‘green procurement’ of such vehicles.

Popular concepts that made it into EEV included:

- CNG, either lean, or stoichiometric or combined concepts (Nylund and Erkkila, 2005)
- Diesel with EGR (MAN, 2008)
- Diesel with EGR and DPF (Evans et al., 2014)
- Diesel with SCR (VOLVO, 2010)
- Diesel with SCR and DPF (HJS, 2013)
- Compression Ignition Ethanol with EGR (Nordstrom, 2007)
- Diesel hybrid

Few numbers of other bus powertrain concepts also appeared in different cities (e.g. Hydrogen, LPG, etc.) but not as mainstream technologies.

Most diesel EEV concepts followed the technological and aftertreatment path that eventually led to Euro V, i.e. utilizing deNO_x aftertreatment but no DPF. However, some initial concepts equipped with DPFs also appeared.

Natural gas buses became very popular with EEV and a number of cities developed the appropriate infrastructure and procured a large number of such vehicles (Evans et al., 2014). Such concepts continue to be popular not just for urban fleets but also for specialised vehicles like airport buses.

Less popular vehicles include the Compression Ignition (Diesel)-Ethanol ones and the latest development, the diesel hybrid buses. Such concepts not only try to achieve low air pollutants emission levels but also to alleviate GHG emissions.

4.6.2. Emission performance

Regulated Pollutants

Delivering a uniform set of emission factors for all EEV buses is not possible because of the completely different concepts, fuels, and emission control technologies utilized. A number of studies have been published where emissions of EEV buses are compared to diesel ones. Admittedly, the most comprehensive studies in Europe for a series of years have been conducted at VTT, where a large number of buses of different technologies and fuels has been tested over a range of driving conditions (Nylund et al., 2004; Nylund and Koponen, 2012). These offer very useful information to compare the different technologies available. Moreover, an early activity from the European Commission on captive fleets, also offers a good background on how different technologies compare to each other in terms of regulated pollutants, energy consumption and GHG emissions, and costs (Ntziachristos and Samaras, 2005). Finally, Hallquist et al. (2013) performed remote sensing measurements of 35 individual buses, 7 of which were EEV CNG ones, including particle number measurements.

Some general points can be made based on these studies in order to understand general emission performance trends of these vehicles:

- Diesel EEVs are on average in par with Diesel Euro V emission factors. Naturally, the exact aftertreatment configuration (EGR, SCR, DPF, and combinations) will have an impact on the emission levels, but this is even the case within the Diesel Euro V category. Early EEV concepts equipped with DPFs (including SCR+DPF) will have better PM performance than Euro V diesel buses.
- CNG (and LPG) buses emit less PM emissions than diesel Euro V, owed to their premixed spark ignition combustion. NO_x emissions depend on the CNG technology: Stoichiometric CNG can be one tenth of Euro V NO_x emissions but lean-burn spark-ignition CNG can be at the same level or even higher than Euro V diesel. In terms of HC, both CNG concepts are several times higher than diesel, with a great fraction of total HC emissions being CH_4 . CO emissions are generally low from all vehicle types.
- A diesel-type (compression-ignition) EEV bus tested on ethanol fuel by Nylund and Koponen (2012) performed relatively better than EEV diesel both in terms of PM and NO_x . However, the differences were marginal and not at a level that would correspond to a significant air quality issue. CO and HC emissions were higher than the diesel levels but at low levels overall. The main benefit of Ethanol therefore appears to be lower GHG emissions if a renewable pathway is followed for Ethanol production.
- In the study of Nylund and Koponen (2012), hybrid buses did not deliver as impressive reductions as it would have been expected judging from the performance of hybrid vs conventional passenger cars. Out of the two buses tested, one was higher and the other one marginally lower than non-hybrid diesel vehicles. A study in US on school bus hybridization (Barnitt and Gonder, 2011) also found negative NO_x impacts for a plug-in hybrid bus compared to a conventional diesel one. The exact calibration of the engine and the aftertreatment components seem to be more important in terms of NO_x control than the hybridization or not of the vehicles. Possibly, hybrid systems may offer further reductions in the future as the technology for buses matures. For example, second generation

hybrid diesel buses in London are considered to lead to 78 % reduction in NO_x over Euro IV, compared to a 21 % reduction of first generation ones (Weston, 2014).

Unregulated Pollutants

Similar to the regulated pollutants, the emission of unregulated components heavily depends on the technology adopted for EEV buses. There are a rather limited number of measurements from such vehicles types. Environment Canada performed a thorough study for some vehicle types and delivered NO_2 and N_2O emission levels which are summarized in the report by Nylund and Koponen (2012). Impressively, in some of the SCR buses tested and over some of the driving cycles, the absolute level of N_2O emissions exceeded the level of NO_x . In general, high N_2O emissions were observed for all diesel buses tests. This has to be given proper attention. With regard to particle number, some emission technologies without DPF also led to high particle numbers. However, the study of Nylund and Koponen (2012) measured the total particle number and not the solid number according to PMP, which is used in this report, that would result to a substantially lower particle number. A non-PMP method to measure particles (i.e. including volatiles) was also used in the study of Hallquist et al. (2013) and again, a large number of particles were found. Total particle number not addressed by the PMP measurement protocol is potentially important for more vehicle technologies, including CNG.

A recent study in London collected a large number of emission ratios for different vehicle types, including EEV buses, using remote sensing measurements (Carslaw and Rhys-Tyler, 2013). The study confirmed the relatively high NH_3 emissions from SCR vehicles as well as marked NO_2/NO_x ratios for EEV SCR buses. Some indication on NH_3 (and N_2O) emission factors from stoichiometric CNG buses are also given in studies of UC Riverside (Hajbabaei et al., 2013; Johnson et al., 2011; Wang et al., 2014). These studies indicate extremely high levels of NH_3 formation from stoichiometric CNG buses. This is not the same for lean burn ones. These high emission factors ought to be confirmed by additional studies in Europe.

4.6.3. Proposed emission factors

Table 23 presents the emission factors of gaseous pollutants proposed for EEV buses of different technologies and Table 24 presents the corresponding particulate emission factors. Several of these emission factors are based on assumptions or a limited number of sampled vehicles, so the following points need to be made:

- The diesel SCR NO_x appears lower than EGR NO_x , despite COPERT and HBEFA assume lower NO_x for Euro V EGR than SCR at urban speeds. The reverse trend presented is based on measured evidence by Nylund and Koponen (2012) and a similar indication by Ligterink et al. (2009) who identified lower NO_x emissions from EEV buses than trucks Euro V at low speeds. Possibly the SCR calibration for EEV buses is different than Euro V trucks and this leads to effective reductions at low speeds.
- The EtOH PN number is derived in proportion to the EtOH PM mass over non DPF diesel ratio. Similarly, the N_2O value is derived in proportion to its NO_x ratio over EEV diesel. The NH_3 emission factor is equal to the diesel w/o SCR.

- The particle numbers presented in this manuscript correspond to solid particles >23 nm. There is little evidence on emissions of this fraction of particles from CNG buses. Many studies have identified high PN emissions from CNG vehicles, and have identified these as mostly volatile particles in the nucleation mode. These are not consistent with the emission factors given in the present report and hence have not been further considered. Therefore, similar (low) values of solid particle numbers are given between diesel+DPF and CNG buses. This will have to be confirmed when more information becomes available.

Table 23: Urban emission factors (g/vkm) of gaseous pollutants proposed for EEV buses of different technology

Driving Mode	CO	HC	NO _x	N ₂ O	NH ₃	NO ₂ /NO _x (wt.)
Diesel EGR (incl. hybrids)	0.20	0.01	7.0	0.050	0.001	CDPF: 0.36 No CDPF: 0.15
Diesel SCR (incl. hybrids)	1.0	0.01	5.7	0.200	0.040	0.10
CNG Stoich. +TWC	1.0	0.8	1.5	0.030	1.00*	0.025
CNG Lean Burn +OC	0.15	2.0	6.7	0.030	0.050	0.40
Ethanol	0.01	0.43	5.5	0.040	0.001	0.035

* Value originating from US technology vehicles. Due to extremely high level, this needs to be verified with European technology vehicles.

Table 24: Urban emission factors of particulate pollutants proposed for EEV buses of different technology

Driving Mode	PM10 g/vkm	PN (×10 ¹¹) #/vkm
Diesel w/o DPF (incl. hybrids)	0.042	2000
Diesel w. DPF (incl. hybrids)	0.011	1.5
CNG Stoichiometric	0.010	1.5
CNG Lean Burn	0.018	1.5
Ethanol	0.036	1700

4.7. Gasoline Euro 3 L-cat vehicles

4.7.1. Description

Gasoline powered mopeds and motorcycles have been the two traditional vehicle types falling under the L-category vehicles. Also, the expression “power two wheelers” has been historically used to describe these two vehicle types. Mopeds are two-wheeled vehicles with an

engine not exceeding 50 cm³ and a speed limited to 45 km/h. In several countries, moped licences are given to youngsters at the age of 16 years old. Motorcycles are larger vehicles, powered by engines exceeding 125 cm³.

In fact, the term “power-two-wheelers” is misleading as mopeds and motorcycles can also be three-wheeled vehicles (L2 and L4 categories, respectively). Sometimes, the word “scooter” is interchangeably used for a moped. In fact, a scooter is a particular vehicle type falling in either the moped or the motorcycle category and it is not defined in the regulations as a separate vehicle category. It is rather a jargon term used to characterize a vehicle style that should correspond to either a moped or a motorcycle used primarily for urban driving. Other jargon terms used for different styles of motorcycles are “street”, “chopper”, “naked”, and others that describe various configurations of the same basic vehicle concept.

With only a few exceptions, gasoline has been the fuel of choice for both vehicle categories, owed to the light-weight construction and the high power-to-volume ratio of gasoline compared to diesel engines. Lately, electric power two wheelers have started to become popular. In China, electric mopeds correspond to the majority of mopeds sold. Several electric scooters have started to appear in the European market as well.

Regulation (EU) 168/2013 extended the L-category gasoline vehicle range to also include on-road or off-road quadri-cycle vehicles, including all-terrain vehicles, quads, buggies, etc. These share similar powertrains with the conventional motorcycles but with distinct differences, mostly focusing on transmission and engine calibration parameters.

The latest emission step for both mopeds and motorcycles has been Euro 3, enforced already since 2006 for motorcycles and only in 2014 for mopeds. Due to the long anticipation of Euro 3 (more than 10 years), late technology Euro 2 mopeds already complied with the Euro 3 standards. The technology of choice to meet the emission limits has been port-fuel injection, stoichiometric combustion (i.e. a lambda sensor) and a TWC for several vehicle types, including both motorcycles and mopeds. The emission control technology is basically the same one utilized in gasoline passenger cars. There are of course differences in the actual implementation, originating from the different emission limits and the type-approval procedure, space and catalyst positioning limitations in a moped/motorcycle, the lack of OBD which means that no catalyst performance monitoring is required, etc. These differences, together with the different driving style of mopeds and motorcycles than passenger cars result in distinct emission patterns between cars and these lighter vehicles.

Moreover, several Euro 3 motorcycles, especially of the smaller sizes, are equipped with a modified version of this stoichiometric concept. In particular, the combustion is adjusted to the slightly rich side to enhance performance and responsiveness. Then, secondary air is injected in the exhaust port before the exhaust reaches a catalyst. The mixture is not precisely controlled to be stoichiometric but the catalyst effectively reduces CO and HC, while NO_x are suppressed in cylinder by the rich combustion. Depending on the catalyst and the tuning, some further NO_x reduction in the exhaust line is possible.

The other combustion technology used for the propulsion of some moped models is two-stroke engines. Two-stroke vehicles have historically been notorious emitters of hydrocarbons mostly for two reasons, i.e. the use of lubricant oil directly in the cylinder, in the absence of a crankcase sump, and the excess scavenging losses due to the overlap in the

exposure of inlet and outlet cylinder ports during charging. Despite emission problems, two stroke engines were popular in the past because they were lightweight, easy to construct and maintain, and had an extremely good power-to-mass ratio. However, meeting the new emission limits means significant investments in the emission control of such engines. This includes electronically controlled fuel injection directly in the cylinder for precise metering of the quantity and the timing of the fuel supplied, secondary air injection in the exhaust line and an oxidation catalyst to control hydrocarbon emissions, and secondarily CO. NO_x are controlled primarily by combustion calibration measures. The new components and the controls of the package make the two-stroke lose some of its edge regarding simplicity, cost and power-to-mass ratio, compared to four-stroke engines. Therefore, two-stroke engines have started to disappear – a trend not expected to revert in the future.

1.1.2. Emission performance

Regulated Pollutants

The latest coordinated actions in Europe to develop emission factors for motorcycles date back already before 2005, when DG JRC completed a measurement campaign on 60 vehicles to support the conversion of the emission limits set over the old driving cycle to the new WMTC (Bonnell et al., 2003) and the FP5 Artemis project developed emission factors based on tests on 115 individual vehicles (Elst et al., 2006). No other study has provided such a comprehensive sample of vehicles since then. However, a number of studies within Europe and in Asian countries have produced emission values for late vehicle technologies and even some earlier ones.

COPERT 4 motorcycle emission are based on the FP5 Artemis project results, together with revisions that were conducted in the framework of the impact assessment study following the Euro 4/5 regulation package (Ntziachristos et al., 2009a). Moped emission factors were recently revised based on a literature review of studies published until 2012 (Katsis et al., 2012), therefore a literature review of studies with regulated emissions of mopeds prior to 2013 is not repeated herein.

Table 25 shows averaged emissions factors for a typical mix of urban (U), rural (R) and Highway (H) conditions for different Euro 3 gasoline L-category vehicles in COPERT. The emission patterns confirm what is known, i.e. high HC emissions from two-stroke vehicles, relatively low NO_x emissions overall, and higher CO emissions from 4-stroke compared to 2-stroke mopeds. The trends for mopeds and the suitability of emission factors proposed in COPERT were confirmed in two studies by TNO (Droge et al., 2011; Hensema et al., 2013). The new moped Euro 3 emission factors proposed in the latest version of COPERT follow on the trends established from previous vehicle technologies and should be considered reliable, at least until new measurements on Euro 3 mopeds are performed.

With regard to Euro 3 motorcycle emissions, COPERT emission factors date back to the 2008 time period. A number of studies in Europe have collected data in tests on chassis dynamometers since then. In Switzerland, Alvarez et al. (2009) measured 10 four-stroke motorcycles over the WMTC cycle and collected data on regulated pollutants. In Italy, several investigators have collected emissions from late technology motorcycles, including measurements over the regulated driving cycles and over patterns better simulating real-world

conditions. The studies of Costagliola et al. (2014) and Zamboni et al. (2011) provide relevant information over hot and cold start cycles for five Euro 3 motorcycles in total. Finally, AECC provided measurements from four Euro 3 motorcycles over the older type approval and the new (WMTC) driving cycles (Favre et al., 2009). These studies provide substantial experimental information to develop reliable emission factors for Euro 3 motorcycles.

Table 25: Averaged emission factors (g/vkm) proposed for gasoline Euro 3 L-vehicles in COPERT 4

Vehicle type	CO	HC	NO _x	PM	Mode (numbers are percentage fractions)
2-stroke moped	1.8	2.05	0.17	0.018	U100
4-stroke moped	2.7	0.79	0.17	0.004	U100
2-stroke motorcycle	2.1	0.58	0.01	0.005	U50, R40, H10
4stroke<250	1.06	0.27	0.10	0.002	U50, R40, H10
4stroke 250-750	1.12	0.30	0.04	0.002	U40, R20, H40
4stroke >750	1.20	0.23	0.07	0.002	U30, R30, H40

Unregulated Pollutants

Limited measurements on unregulated pollutants have been conducted on motorcycles and mopeds. In fact, the emphasis on unregulated pollutants from such vehicles mostly focuses on characterisation of their HC profile. This is justified given the high HC emissions, especially from two-stroke vehicles. With regard to the unregulated pollutants of interest to this study, Clairotte (2014) provides a full characterisation of pollutants from a single Euro 2 moped while Favre et al. (2011) provides PN emissions for four mopeds.

Particle numbers from mopeds, and in particular two-stroke ones – appear very high. This is the result of the incomplete mixing of the fuel and the partial combustion of lube oil in the cylinder. The limited information that exists with regard to the other pollutants basically confirms the general trends of non regulated pollutants identified for gasoline passenger cars.

4.7.3. Proposed emission factors

The emission factors of regulated pollutants presented in COPERT for mopeds are based on a recent literature review and the levels established are confirmed with the latest measurements that have become available. The latest information collected on motorcycle emission factors though shows that COPERT CO emission factors are appropriate for hot cycles but need to be increased to include cold-start. Moreover, NO_x emission factors also appear rather low, compared to the latest measurements. With these considerations, and with processing of the information collected from the latest European motorcycle studies, aggregated emission factors for Euro 3 motorcycles, without distinction to vehicle size and including the effect of cold start are shown in Table 26 for gaseous pollutants and in Table 27 for particulate pollutants.

Table 26: Proposed emission factors (g/vkm) of gaseous pollutants for Euro 3 mopeds and motorcycles

Vehicle type	CO	HC	NOx	N2O	NH3	NO2/NOx (wt.)
2-stroke moped	1.8	2.05	0.17	0.002	0.005	0.05
4-stroke moped	2.7	0.79	0.17	0.002	0.015	0.05
2-stroke motorcycle	2.1	0.58	0.01	0.002	0.005	0.05
4stroke motorcycle	2.4	0.24	0.15	0.002	0.020	0.05

Table 27: Proposed emission factors of particulate pollutants for Euro 3 mopeds and motorcycles

Vehicle Type	PM10 g/vkm	PN ($\times 10^{11}$) #/vkm
2-stroke moped	0.018	300
4-stroke moped	0.0040	80
2-stroke motorcycle	0.0050	90
4stroke motorcycle	0.002	12

4.8. Diesel Euro 3 L-cat vehicles

4.8.1. Description

The extension of the L-vehicles category to new vehicle types also provided room for diesel powered vehicles. Although diesel combustion overall contributes very little to the power-trains utilized in this category, it is particularly popular to a certain vehicle category, i.e. micro-cars (L6 and some L7 vehicle categories). Micro cars are quadri-mobile vehicles powered by small engines, primarily below 6 kW. They are smaller than M1 vehicles and rather underpowered but they offer ease of use and versatility as well as a more playful character. In many countries, youngsters at the age of 16 can get a driving licence for such cars, similar to the legislation for mopeds. Therefore, such cars have become popular as an alternative to motorcycles and mopeds. This may be because they are easier to drive, they do not need specialised gear and offer protection from weather elements. Diesel engines may also be used for some of the L5e-B vehicles, which are tricycles used for delivery of goods. We will collectively address them in this report as diesel micro-cars.

The emission regulation was so far very relaxed for these vehicles, owed to their limited market size and hence their overall low environmental impact. This allowed them to be powered by small, mostly generator-type of diesel engines. These engines are properly retunes to offer a dynamic range (compared to their single mode operation when used as generators) and are fitted to the vehicles to provide the low power allowed by the regulations. No aftertreatment or particular engine measures were required to control emissions. This contributed in offering a small, reliable, and economical powertrain package. As a result, it is estimated that some 70% of the small market of these micro-cars (~25 k units annually) are diesel powered (Ntziachristos et al., 2013). A growth in the market of these vehicles is expected in the years to come, together with an increasing contribution of electric vehicles in the sector.

4.8.2. Emission performance

Regulated Pollutants

Current technology vehicles are regulated only at a Euro 2 level, which became applicable in 2003 with Directive 2002/51/EC. This set emission limits of 2.0 / 1.0 / 0.65 g/km of CO / HC / NO_x, respectively, that is more or less in line with passenger car Euro 2 NO_x emission factors and even more relaxed limits for CO and HC. No study could be located with specific measurements of emissions from these vehicle types. The emission factors proposed for those vehicles originate from work conducted within the MCWG committee of the European Commission and in particular the study performed to support the impact assessment of further emission controls to L-category vehicles (Ntziachristos et al., 2009a). Moreover, in the absence of more reliable information, type approval data of diesel L-vehicles have been taken into account.

Unregulated Pollutants

No studies on unregulated pollutants from micro-cars are known. Therefore, the emission factors proposed originate from COPERT Euro 2 diesel passenger cars. An aggregated version of these emission factors can be found in the Transphorm database, and these values are also included in this report.

4.8.3. Proposed emission factors

Proposed emission factors for diesel micro cars are shown in Table 28 for gaseous pollutants and Table 29 for particulate pollutants.

Table 28: Proposed emission factors (g/vkm) of gaseous pollutants for diesel micro-cars

Driving Mode	CO	HC	NO _x	N ₂ O	NH ₃	NO ₂ /NO _x (wt.)
Urban	0.93	0.15	0.81	0.003	0.001	0.11

Table 29: Proposed emission factors of particulate pollutants for diesel micro-cars

Driving Mode	PM10 g/vkm	PN (×10 ¹¹) #/vkm
Urban	0.15	2000

5. Upcoming Vehicle Technologies

5.1. Euro 6c cars

5.1.1. Description

The high NO_x emissions of Euro 5 diesel cars initiated a series of measures to make sure that future emission control technologies will provide the reductions promised by the emission limits also over real world operation. The most important new step in this direction has been the introduction of RDE testing in the 2017/18 time horizon, as presented in section 2.1.4. Successful implementation of this new regulatory tool may indeed safeguard against intentional or unintentional exceedances of the emission limit. It is expected that RDE testing will in fact be an entirely new step into lower diesel NO_x at Euro 6c level.

The second significant change with Euro 6c refers to the strict control of PN from GDI vehicles. The limit is brought down by one order of magnitude, from $6 \times 10^{12} \text{ km}^{-1}$ for Euro 6 GDI cars down to $6 \times 10^{11} \text{ km}^{-1}$, that is at a similar level with diesel cars.

Emission factors may also be affected by the strict OBD thresholds introduced at Euro 6c level, which have been proposed to safeguard long-term effectiveness of the emission control system. An OBD has two functions: first, to detect failures that may sporadically appear due to defects or a mistreatment of the vehicle; second, to monitor that the normal ageing of the emission control system remains under controlled levels. It is difficult to predict how much new OBD regulations will affect the average emission factor level. This is an area where more attention should be given by future research and policy assessment studies.

5.1.2. Emission control technology

The RDE introduction for diesel NO_x will have significant repercussions to diesel vehicle emission control. Although the main systems to control emissions will continue to be the ones implemented also at a Euro 6 level, i.e. EGR, LNT, and SCR, a new calibration and control strategy of the whole system is expected. EGR will have to be extended over a wider engine operation range to cover conditions outside of the confined NEDC area. However, EGR at high load/high speed conditions may affect power output, fuel consumption and overall performance. Therefore, in contrast to Euro 6, most, if not all of, diesel Euro 6c vehicles will need to be equipped with specific deNO_x aftertreatment, on top of EGR.

SCR today appears as a mature technique that can achieve the required reductions. Euro 6 cars that utilize SCR have been shown to exhibit much lower NO_x levels than Euro 5 cars, also in real-world conditions (Weiss et al., 2012). However, they do remain much above limits in real-world conditions. Higher reductions can be achieved by increasing the urea dosage and better tuning of the system. Manufacturers try to avoid this so that urea replenishment does not become necessary in-between regular service intervals. This is considered a nuisance for the user (driver or vehicle owner). At Euro 6c, either larger urea tanks or more frequent urea replenishment than Euro 6 will be required, similar to the changes occurred in Euro VI over Euro V diesel trucks. SCR also requires relatively high temperature for efficient operation. Maintaining high temperature at urban driving results into a fuel consumption penalty. In order to avoid this, the combination of EGR+SCR is necessary.

It may be expected that some smaller vehicles may continue to meet the limits without SCR, i.e. by utilizing LNT+EGR and engine tuning towards high PM/low NO_x operation. This is because SCR packaging may be technically more difficult for smaller powertrains but also in order to reduce costs. On the other hand, such an engine/aftertreatment combination is deemed to increase fuel consumption over the SCR alternative.

With the enhanced fuel efficiency of GDI engines, which now become available even for economical gasoline cars, the diesel engine is going to be significantly challenged at Euro 6c level. It is probable that the diesel model distribution will be shifted to larger, and more expensive, passenger cars.

With regard to gasoline vehicles, the most significant changes are expected for GDI engines. Most of the GDI vehicles today have been seen to fail reaching the 2017/18 time PN limits. In the recent study of May et al. (2013), actually one Euro 5 car out of the five measured was just below the 2017/18 PN limit. Unpublished results at DG JRC also show that some current GDI models can already reach the PN levels of the Euro 6c standard. The expectation is though that several of the GDI cars will necessitate gasoline particle filters (GPF) to reach the limits (Mamakos et al., 2013b). Current research focuses on the combination of a TWC and a GPF (Richter et al., 2012) for Euro 6c GDI and commercial systems have already started to appear.

CO₂ emission regulations will also have some repercussions to air pollutant emissions. GDI vehicles (together with hybrid vehicles) are expected to become more popular as a consequence of their better fuel efficiency in comparison to conventional gasoline cars. This will lead to a shift of overall gasoline car emissions to more GDI-like performance (Rexeis et al., 2013). However, the change from NEDC to WLTC – which is characterised by lower idling periods – may actually stabilize the penetration of start and stop systems to the market. Both these trends will reflect on the average air pollutant levels from Euro 6c gasoline vehicles.

5.1.3. Proposed emission factors

With regard to diesel NO_x emissions, Rexeis et al. (2013) propose a reduction of 47 % in comparison to Euro 6 level, which has also been retained in this report for consistency. The reduction is calculated assuming that the actual emission level of Euro 6c cars (expressed as the average of the ARTEMIS driving cycles) will be twice as high as the emission limit as such (i.e. at 160 mg/km). No other change to gaseous and particulate pollutants has been introduced. Due to the increased implementation of SCR, we also make the assumption in this report that N₂O and NH₃ emissions will increase by the same proportion (i.e. by 47 %) over Euro 6 levels. The NO₂/NO_x ratio also remains constant. The expected gaseous pollutant emission factors for diesel Euro 6c with these considerations are shown in Table 30. No changes of particulate emissions (PN and PM) over Euro 6 diesel levels are expected.

No change to gaseous air pollutants is proposed for Euro 6c gasoline cars, over Euro 6. In fact, marginal changes may occur due to the different penetration of GDI vehicles and the differentiation of the emission profile compared to PFI ones, presented before. However, the change in average levels is expected to be only marginal. The only difference will be the par-

title number emissions from GDI cars. For simplicity, we can assume that the PN levels from the mix of PFI and GDI vehicles at Euro 6c will be indistinguishable from the average PN emission level of Euro 6 PFI cars (Table 12).

In case that a combined TWC+GPF catalyst is used, it is interesting to explore its impact on non regulated pollutants and, in particular, NH_3 . No evidence of the performance of such a system on non regulated pollutants exists today.

Table 30: Proposed emission factors (g/vkm) of gaseous pollutants for Euro 6c diesel light duty vehicles

Driving Mode	CO	HC	NO _x	N ₂ O	NH ₃	NO ₂ /NO _x (wt.)
U	0.085	0.050	0.16	0.015	0.010	0.30
R	0.055	0.040	0.15	0.0055	0.010	0.30
H	0.066	0.029	0.23	0.0055	0.010	0.30

5.2. Battery and fuel-cell electric vehicles

5.2.1. Description

Battery electric (BEV) and fuel cell (FCEV) vehicles have been considered as advanced technology options to reduce greenhouse gas and air pollutant emissions. Such vehicles comprise an all-electric powertrain, where power to the wheels is provided solely by conversion of electric to mechanical power. The difference of the two concepts is in the way that energy is stored on the vehicle.

In BEVs, energy is stored in the form of electricity in batteries on board the vehicle. When needed, electric power from the batteries feeds an electric motor, which in turns powers the wheels. Batteries have been so far the limiting factor in the growth of the BEV market due to their inferior energy density compared to liquid fuel, high cost, and question-marks on their long-term performance. A typical state-of-the-art (Li-ion) battery package which provides an autonomy range of 100-200 km to a medium sized electric vehicle typically costs around k €10 and weighs in excess of 200 kg (Ntziachristos and Dilara, 2012). This almost doubles the price of the vehicle over a conventional powertrain. Charging considerations and the associated infrastructural and behavioural changes of vehicle owners also provide an obstacle in widening the popularity of BEVs. On the other hand, electric vehicles offer low operational costs, high overall efficiency, ease of operation, and driving and noise comfort. A significant penetration of electric vehicles in the real world will therefore only take place when the technical and cost competitiveness of batteries improves. Technological maturity and material limitations delay this. New breakthroughs in battery technology, possibly involving non Li materials, will be required.

In order to overcome some of the issues of BEVs, FCEVs are advantageous in that energy can be stored on board the vehicle in a liquid form. Most often hydrogen is the main energy carrier, stored either compressed in high pressure tanks or adsorbed on a storage material. The energy carrier is converted to electricity in a fuel cell, also on board the vehicle. The

electricity produced is then used to power the wheels in a more or less identical fashion to the one implemented in BEVs. In fact, as fuel cells are not able to respond to sudden power demand changes, batteries are also used in parallel to the fuel cell unit to cover instantaneous power needs. In FCEVs, batteries are much smaller in size than in BEVs and are recharged by the fuel cell in periods of reduced power demand. There is only one vehicle model commercially available today in US that utilizes a hydrogen fuel cell powertrain (Honda FCX Clarity) while Toyota recently announced a new fuel cell vehicle to become commercially available around the world in 2015.

The limiting factor in this vehicle technology is the non-availability of hydrogen, both with regard to its production and refuelling infrastructure. Hydrogen is not a primary energy source but has to be produced utilizing one of the existing power sources. It then has to be distributed locally, and then stored on board the vehicle. The whole process is technically demanding due to the diffusivity and safety concerns related to the use of gaseous hydrogen. Significantly advancing the presence of FCEVs on the road will require major investments in the so-called hydrogen economy front, which includes hydrogen production, distribution, storage, and refuelling considerations.

FCEVs may also operate on alternative to hydrogen fuels in two different pathways. One option is to use methanol directly in a specially designed fuel cell (direct methanol fuel cell), which operates similarly to the hydrogen one but with a lower overall efficiency. The second option is to use almost any conventional fossil hydrocarbon fuel on a reformer where fuel reacts with steam over a catalyst to separate hydrogen from carbon atoms. Hydrogen is then used in a conventional fuel cell. Demonstration vehicles of both these concepts have appeared, e.g. the Daimler NECAR 5 utilizing a direct methanol fuel cell vehicle, and Toyota FCHV-5, utilizing a gasoline reformer.

5.2.2. Emission performance

BEVs and FCEV-s are known for their zero tailpipe emission production. BEVs have no tailpipe and are true zero emitters, at least with regard to emissions produced by their propulsion system. They still produce primary particles due to tyre and brake attrition and increase ambient concentrations of PM due to re-suspension of road dust, similarly to conventional powertrain vehicles.

Emissions of FCEVs can actually range from zero to measurable levels. Hydrogen fuel cells only produce steam, as a product of the reaction of water with oxygen. FCEVs equipped with on-board reformers will however emit measurable quantities of CO and VOCs (and of course CO₂), which will depend on the exact technology, in particular over start-up and transient operation of the reformer. Given the extremely low CO and, in particular VOC, emission limits in US and Europe, not all fuel cell vehicles should be considered low emitters. For example, Thomas et al. (2000) estimate 24 mg/mile of VOC+NO_x for a methanol FCEV which is on the limit of the upcoming Tier 3 limits in US (30 mg/mile). Therefore, FCEVs should not necessarily be considered zero emitters but low emitters, compared to conventional cars.

Most importantly than on-board or tailpipe emission production, upstream or so called well-to-tank emissions are the most important contributors to total emission production for elec-

tric vehicles. This holds true both for BEVs and FCEVs. In particular for BEVs, the feedstock used for electricity entirely determines the implied emissions from electric vehicles. Most of the analyses so far have focused on the impact of BEVs on total GHGs and the long list of literature studies available show that lifecycle emissions of BEVs taking into account fuel production, conversion, and vehicle production can range from much higher, on par or even much lower than conventional cars, depending on what energy mix is considered in each case. We do not further discuss this issue here as this is not so much an issue of car technology but rather an issue of local energy industry structure, vehicle-to-grid infrastructure, etc. The reader is therefore directed on several books and papers that look into this matter around the world.

However, it is also important to consider that energy production in the form of electricity or liquid fuel for electric vehicles may also produce substantial amounts of conventional air pollutants. These are produced either by the power stations producing electricity, or local stationary reformers producing hydrogen, or processes converting e.g. natural gas to methanol, and similar procedures. Estimating the implied vehicle emission factors that such procedures result to is again a complicated process that depends a lot on the local energy mix and the exact energy conversion processes followed. In any case, when upstream energy generation is put in perspective, then BEVs cannot be considered as zero emitters any more. An example of an analysis using the current US energy production showed that BEVs are marginally better in terms of NO_x and much worse in terms of $\text{PM}_{2.5}$ and SO_x compared to current conventional vehicles (Cai et al., 2013). Sioshansi and Denholm (2009) found some decrease in NO_x when plug-in hybrid vehicles were introduced in Texas road transport but a large increase in SO_x .

In designing an integrated air quality policy involving electric vehicles, one therefore needs to consider energy and fuel production associated emissions (either on-board the vehicle or upstream ones) and not just make the usual simplification that electric vehicles are zero emitters. The exact local energy generation mix, the technology used for energy conversion as well as the proximity of power generation stations to cities – where most of the air quality problems reside – are different dimensions of the issues that have to be considered in this process.

5.3. Future L-category vehicles

5.5.1. Description

Regulation (EU) 168/2013 has set aspirational targets for the emission limits of future L-category vehicles. These are shown for the most popular types of L-category vehicles in Table 31. Euro 5 limits bring light duty vehicle emission limits at the same numerical level with passenger cars. Actually, these need to be met over a more demanding driving cycle by L-category vehicles (WMTC), than passenger cars (WLTC). Therefore, the numerical limits proposed for Euro 5 L-category vehicles today correspond to the most stringent standards of all vehicle categories in Europe. The three most important changes brought by the Euro 5 over the current levels include the drop of HC for mopeds by more than six times, a similar six-fold drop in NO_x for diesel mini-cars and an almost 20-fold drop of PM emissions from mini-

cars. In fact, the moped reductions requested for CO and HC are even more severe than what Table 31 shows, because the type approval value is calculated with 30/70 weighing of the cold and hot phases of the driving cycle at Euro 4 level and this becomes 50/50 at Euro 5. According to Regulation (EU) 168/2013, these values will need to be confirmed by an environmental study to be completed by 2015. However, no significant deviations of the final values from the already proposed numerical levels are expected.

Table 31: Emission limits for most popular future L-category vehicles (g/vkm)

Category	Euro level	Year of implementation*	CO	HC	NO _x	PM
Gasoline Mopeds (L1e-B)	Euro 3	2002	1	1.2 (HC+NO _x)	-	
	Euro 4	2017/2018	1	0.63	0.17	-
	Euro 5	2020/2021	1	0.1	0.06	-
Gasoline Motorcycles						
(L3e)	Euro 3	2006	2,62	0.75 (v<130 km/h)		
0.33 (v≥130km/h)	0.17 (v<130 km/h)					
0.22 (v≥130km/h)	-					
	Euro 4	2016/2017	1.14	0.38 (v<130 km/h)		
0.17 (v≥130km/h)	0.07 (v<130 km/h)					
0.09 (v≥130km/h)	-					
	Euro 5	2020/2021	1	0.1	0.06	-
Diesel micro-cars						
(L5e-B, L6e, L7e-C)	Euro 2/3	2003	2.0	1.0	0.65	-
	Euro 4	2017/2018	1.0	0.1	0.55	0.08
	Euro 5	2020/2021	0.5	0.1	0.09	0.0045

*New types/existing types

5.3.2. Emission control technology

The emission limit values in Table 31 make clear that advanced emission control technology will be required for compliance in future vehicles of this category. Already the Euro 4 limits will require the extensive use of three way catalysts and stoichiometric combustion for motorcycles, while larger catalysts and overall better strategies will be requested for

mopeds. In particular, the introduction of a cold-start means that better thermal management will be required for faster catalyst light off. Diesel vehicles will require an oxidation catalyst to control PM emissions and improved combustion tuning to control NO_x emissions. Fuel metering and injection pressure will also need to be more precisely adjusted. However, Euro 4 is not expected to require any technological breakthroughs to achieve, rather normal engineering improvements over the previous stage.

Euro 5 however will require significant technological investments to materialize. This is not only the consequence of the reduced emission limit values but also the combined impacts of the enhanced durability and OBD requirements. For gasoline vehicles, this will require strict enforcement of stoichiometric combustion and an efficient three way catalyst, optimally positioned to reach the limits. Reaching the limits over the WMTC, instead of the NEDC of today's passenger cars, means that the quality and packaging of the whole system should actually be better than current Euro 6 gasoline passenger cars. This is not expected to be a limiting factor for some of the expensive high-end L3 motorcycles. The cost and space limitations for smaller vehicles may though become a limiting factor in that case. The extreme case would be mopeds, which will require closed loop control of the TWC, positioning of the catalyst close to the engine outlet (or dual layer exhaust line) for fast light-off, twin lambda sensors for long term performance verification of the emission control devices, etc. The whole package is expected to significantly increase the end price of mopeds, to the point that larger vehicles become much more competitive in terms of value for money.

The situation becomes even more challenging for diesel mini-cars. The Euro 5 emission limits are set at the same level of Euro 6 diesel passenger cars. This means that the same emission control technology will be required, including electronically controlled ultra-high pressure fuel injection, exhaust gas recirculation, and a diesel particle filter with active regeneration to guarantee compliance with the emission limits. It is not yet known whether this technology will be competitive, given the significant costs it implies. Gasoline or electric vehicles would become much more cost efficient than diesel ones at a Euro 5 stage.

5.3.3. Proposed emission factors

The proposed emission factors at a Euro 4 level for regulated pollutants are mostly based on the emission limit reductions between Euro 4 and Euro 3, taking into account the difference in the consideration of cold-start for mopeds. The emission factors for non regulated pollutants follow engineering assessments of the technological developments in each case. For gasoline vehicles, this means oxidation catalysts with the tendency to form more ammonia while for diesel vehicles, the NO_2/NO_x ratio will be increasing as the tailpipe environment becomes more oxidative. With regard to particle emissions, two-stroke engines correspond to only a small fraction of the market by Euro 4 and become obsolete at Euro 5. For diesel cars, DPFs substantially reduce emissions at a Euro 5 level.

Table 32: Proposed emission factors (g/vkm) of gaseous pollutants for future L-category vehicles

Vehicle Type	CO	HC	NO _x	N ₂ O	NH ₃	NO ₂ /NO _x (wt.)
Euro 4 Moped	1.8	1.1	0.17	0.002	0.015	0.05
Euro 5 Moped	1.5	0.17	0.060	0.002	0.020	0.05
Euro 4 Motorcycle	1.3	0.18	0.072	0.002	0.020	0.05
Euro 5 Motorcycle	1.1	0.09	0.048	0.002	0.020	0.05
Euro 4 Diesel Micro-car	0.47	0.08	0.69	0.005	0.001	0.20
Euro 5 Diesel Micro-car	0.23	0.08	0.15	0.010	0.001	0.40

Table 33: Proposed emission factors of particulate pollutants for future L-category vehicles

Vehicle Type	PM10 g/vkm	PN (×1011) #/vkm
Euro 4 Moped	0.0050	100
Euro 5 Moped	0.0008	3.0
Euro 4 Motorcycle	0.0025	3.0
Euro 5 Motorcycle	0.0007	3.0
Euro 4 Diesel Mini-car	0.0800	1500
Euro 5 Diesel Mini-car	0.0030	6.0

5.4. Alternative and future fuels

5.4.1. Description

Currently used mainstream fossil fuels include gasoline and diesel, that correspond to ~93 % of all energy used in road transport (EC, 2014). Through subsequent regulations of fuel specifications, diesel and gasoline grades of today are high quality products with only traces of impurities like sulphur and a chemical character which well serves the needs of advanced combustion and aftertreatment systems used in on-road vehicles. As a result, current fuels enable technologies that can lead to extremely low – below ambient concentrations – emissions of air pollutants. With the current status of aftertreatment technology, no additional significant emission reductions of regulated pollutants can be expected by further control of conventional fuel specifications, with perhaps the exception of the fuel performance in cold (sub-zero) conditions.

On-going scientific research and regulatory efforts in the production and promotion of ‘alternative’ fuels mainly stem from energy security considerations and the need to reduce GHG from transport. Communication ‘COM(2013) 17 final’ from the European Commission to the Parliament designates the main alternative energy sources for transport, and road transport in particular, to be LPG, natural gas, electricity, liquid biofuels and hydrogen. All of these fuels are already used in road transport, in various extents and degrees of success.

Air quality implications of each fuel type largely depend on the main fuel specifications, which in turn depend on the feedstock or primary energy source used for their production. There are four different pathways for the production of alternative and future fuels, summarized in the following list:

- **Petroleum refinement by-products:** The process of petroleum refinement can provide additional diesel-like or gasoline-like alternative fuels by means of secondary processing of the lighter or heavier distillation extracts. LPG is a by-product of petroleum (crude oil or natural gas) refinement. Catalytic cracking of heavy oil residues may also lead to lighter liquid components.
- **Natural gas products:** Natural gas can be directly used on an engine or can also be converted to more energy dense (liquid) products to enable easier refuelling and storage on board the vehicle. Typical natural gas derivative fuels are methanol and dimethylether (DME).
- **Biofuels:** The so-called first generation biofuels correspond to the most widespread alternative energy source in road transport, accounting for 4.7 % of total energy consumption in EU's transport by 2013 (Euroobserver, 2014). Second generation biofuels are currently under focus. These are not based on food crops, they are produced with techniques that have a reduced carbon footprint compared to conventional biofuels and should result to products that are compatible to today's conventional fossil fuels.
- **Electricity and hydrogen:** Electricity and hydrogen should both be produced from renewable energy sources to meet the required sustainability criteria. Their use takes place in electric vehicles with specifically designed powertrain systems (battery electric or fuel-cell electric) that result to zero emissions by the vehicle but are linked to upstream emissions.

5.4.2. Emission performance

Several of the individual alternative fuels are already used at various degrees on current road vehicles. Some of them, like biofuels, LPG, and CNG have successfully substituted a measurable portion of diesel and gasoline, while some others (like H₂ or even electricity) are still used in niches.

The impacts of several of the alternative fuels to air pollutant emissions have been discussed in the previous sections. The impacts observed are not only a function of the fuel used but a combination of fuel and vehicle type and emission control technology. For example, natural gas can be used in passenger cars to replace gasoline but also as an alternative to diesel buses. The relative emission impacts are different in each case.

Instead of repeating emission impacts, this section deals only with these fuel/technology combinations not addressed in the previous sections. The intention is not to provide quantified emission factors, but only the most important qualitative impacts over reference fuel-emission control technology combinations.

LNG vs CNG

Often, confusion is created between liquefied natural gas (LNG) and compressed natural gas (CNG) with regard to their combustion characteristics. It should be clarified that these two

forms of natural gas refer only to the way that the fuels are stored on board the vehicle. The confusion may be created as liquefied petroleum gas (LPG) can be injected either in liquid or gaseous form in the cylinder. This is not the case with LNG, as its cryogenic temperature does not allow its liquid injection. Rather, LNG is first vaporized and then injected, in a similar manner to CNG. Therefore, the combustion of the two forms of natural gas is identical and hence also results to identical emission profiles.

Methanol and DME combustion

Methanol is more of a historic rather than future fuel, as it has been used for decades in particular in US as a gasoline replacement. It can be produced from natural gas, coal gasification, or biogas, using various synthesis techniques. New natural gas resources in US renewed the interest in its application, while in Europe it is considered both as a fuel derived from natural gas and/or biogas (Riaz et al., 2013). Methanol has a high natural octane rating (>105) and offers additional efficiency gains due to its high heat of vaporization. Methanol is ignited in cylinder by a spark, in an identical process to gasoline combustion. Hence, emissions are controlled by a three way catalyst and a similar profile of conventional pollutants as gasoline is to be expected. As with other alternative fuels, retaining stoichiometry with methanol can be tricky and requires appropriate calibration of the lambda sensor to guarantee that stoichiometry is reached regardless of the methanol/gasoline blend used (flex-fuel vehicles). Similar to ethanol and other alcohols, oxygenated organic compounds like aldehydes and ketones can be a problem when methanol is combusted but, on the other hand, its use may result to a reduction of aromatic and polyaromatic products of gasoline combustion.

In a nutshell, use of methanol instead of gasoline on new, specifically designed vehicles is not expected to lead to substantially different levels of air pollutants, as long as oxygenated compounds are satisfactorily dealt with. It also offers the potential for the reduction of aromatic (including poly-aromatic) species in the exhaust. However, use of methanol in existing vehicles may lead to slight departures from stoichiometry, in a similar way to LPG retrofits. Methanol can also be aggressive to some of the engine parts, if no proper care is given, thus creating additional failures and, possibly, secondary air emission impacts.

When two molecules of methanol are dehydrated and combined, they produce the simplest ether, dimethylether (DME). DME is gaseous in ambient conditions but will become liquid, to increase its specific energy content, when compressed at a moderate pressure. DME can be an excellent diesel fuel replacement due to its high natural cetane number (55) and low auto-ignition temperature (Park and Lee, 2013). Volvo has opted for DME in addition to natural gas as a commercial alternative fuel replacement for its diesel trucks in US, starting 2015. Because of its highly oxygenated character, DME combustion results to soot levels that can meet Euro VI limits (or the equivalent US2010) without the need of a DPF. Currently, SCR is required to reduce NO_x in DME trucks. Therefore DME trucks are expected to offer similar or better NO_x and PM performance compared to the latest diesel technologies. The absence of a DPF may result to a higher particle number than DPF-equipped diesel ones.

H₂ combustion

Hydrogen is an ideal fuel for fuel cell electric vehicles and can result to zero vehicle emissions, as discussed in a previous section. However, one manufacturer (BMW) has for long been considering an alternative pathway for H₂ utilization, that of its combustion in an internal combustion engine. Although this approach is heavily criticised in terms of its sustainability, the small number of commercial vehicles produced (BMW Hydrogen 7) demonstrate that H₂ combustion can result to similar operation and performance characteristics to those of gasoline. The particular vehicle actually carries both fuels and can operate on either a H₂-mode or on a conventional gasoline mode (the latter one of reduced power compared to the gasoline-only version of the same engine).

In terms of conventional pollutant emissions, hydrogen combustion is free of CO and any traces of HC emissions are due to lube oil consumption. However, NO_x emissions can be significant due to the high combustion temperature of H₂. Specifically tuned combustion and coupled NO_x aftertreatment is required to reduce NO_x emissions from the only commercial hydrogen combustion vehicle available today. With such advanced technology implemented, even H₂ combustion can be a very low (practically zero) contributor to air pollutant emissions (Wallner et al., 2008). However, hydrogen combustion should not be considered 'clean' by definition, especially in terms of NO_x.

2nd Generation biofuels

First generation biofuels (FGB) have been the most significant alternative source of energy, contributing to almost 5 % of total road transport energy consumption in Europe. There has been a very large literature on impacts of biofuels on conventional pollutant emissions. Kousoulidou et al. (2012) summarized the biodiesel studies applicable to European passenger cars and found that the impact of biodiesel blends up to 7 %, as specified by the regulations, lead to less than 10 % effect on NO_x (upwards) and PM (downwards). A review by Katsis et al. (2012) on bioethanol effects also found negligible impact (up to 4 %) on NO_x emissions from E85 flex-fuel vehicles. Moreover, current E10 blends on conventional vehicles have also been shown to lead to vehicle-specific impacts on NO_β, but with no significant impact on a fleet-wide level (Karavalakis et al., 2012). Overall, and speaking in terms of current blending ratios and on average over Europe, the introduction of FGBs did not lead to substantial positive or negative impacts to the average emission level of vehicles.

Second generation biofuels (SGBs) started to appear since a few years already. Although a strict definition does not exist, SGBs are understood to be those fuels produced from non food-competitive biomass, utilizing advanced sustainability production techniques. Such production techniques aim at producing fuels which are fully compatible with existing diesel or gasoline and with the potential to be used either neat or in blends with conventional fuels. In neat form (or even in high blends with conventional fuels) these fuels may have positive or negative impacts on pollutant emissions from current vehicles, depending on their formulation. For example, renewable diesel produced by hydrotreating and not esterification of vegetable oils may produce diesel-like hydrocarbons that have been shown to lead to measurable emission reductions from current diesel heavy duty vehicles (Happonen et al., 2013). Similar to other fuels, SGBs are expected to have a large impact in terms of air pollutant emissions to legacy vehicle types and not to latest vehicle technologies with advanced aftertreatment. Monitoring the impact of SGBs in terms of both regulated and unregulated pollutants needs to be conducted with reference to the vehicle technology they are used to.

6. Assessment of emission factors proposed

6.1. Uncertainties

Road vehicle emission factors are prone to large uncertainties due to the multitude of operational and environmental conditions that every vehicle is exposed to. Inventorying assessment methodologies have designated the uncertainty in the emission factors as a key parameter in the uncertainty of the complete inventory (Kioutsioukis et al., 2010; Kioutsioukis et al., 2004).

The emission factors proposed in this report are also bound to uncertainties. Therefore, the question arises what is the expected error when such emission factors are to be used. Providing an exact quantified response is not possible, in particular given the fact that several of the emission factors proposed are the result of an engineering assessment or they are based on a limited number of measurements.

It should first be highlighted that the emission factors proposed in this report (and in most similar reports and studies) try to represent average emissions of the complete vehicle fleet and not of individual single vehicles. Vehicles falling under the same type, fuel, and emission standard may substantially differ in terms of their real-world emission performance because of different realisation and tuning of their emission control systems. When an uncertainty range is proposed for an emission factor (e.g. at a 95 % confidence level) this does not mean that 95 % of the vehicles of the particular type will be within the uncertainty range proposed. It rather means that there 95 % chances that the average emission level of the complete vehicle fleet for the inventory considered will be within the range proposed.

This is important to understand. Several times, experimental studies based on a handful of measurements are used to validate emission factors used in emission models. By measuring a small number of vehicles, they often come to the conclusion that the model ‘underestimates’ or ‘overestimates’ emissions by a certain percentage. This is misleading. The precise expression would have been that the model prediction and the emission level of the vehicle sample employed in the particular study “deviate” by certain percentage. This indeed could be because of model error or because of the small sample used in that study or, most probably, for both reasons. Typically, it takes some 50 individual passenger cars and 10 individual heavy duty engines or vehicles of the same type to develop reliable fleet-level emission factors. Trying to validate such emission factors with a much smaller sample is questionable.

This does not mean that all emission factors contained in models and that all emission factors contained in this report are of the same quality and reliability. Emission factor databases need to be complete which means that some of the values contained are approximations only, not even based on a single measured value. Such values are also contained in this report. In such cases, even a small vehicle sample may produce an average value which is better than the approximation used.

Emission factors correspond to a particular operation condition or mix of operation conditions. Using or trying to validate the emission factors outside of their designed range of application will most probably not be satisfactory because of the variability of vehicle emis-

sion performance depending on the environmental conditions. The emission factors proposed in this report are only distinguished into urban, rural, and highway driving. Typical operation patterns are assumed in each case. The urban emission factor includes cold start (where this is important) and fuel evaporation is added to the hydrocarbon emissions of gasoline passenger cars. Also, the impact of ageing on emission levels is added. Driving pattern effects, the impact of low temperatures, or the impact of failures cannot be revealed by the emission factors proposed.

By taking into account these considerations, the following empirical guidance can be given on the emission factors proposed, largely based on similar guidance provided in the Atmospheric Emission Inventory Guidebook (Ntziachristos and Samaras, 2013):

- Emission factors for regulated pollutants (CO, HC, NO_x, and PM) of key existing vehicle technologies are known with good confidence. An estimated uncertainty would on average be $\pm 30\%$ of the mean value proposed. As said before, it is still difficult to statistically determine this uncertainty, so the range quoted should be seen as an empirical assessment.
- Emission factors of unregulated pollutants (NH₃, N₂O, NO₂/NO_x, and PN) are known with less certainty and are mostly designed to give an order of magnitude level of the vehicle emissions. Order of magnitude uncertainty range should also be considered for regulated pollutants of less popular vehicle types (e.g. diesel micro-cars, Ethanol buses, etc.)
- Emission factors for future vehicle technologies (e.g. Euro 6c LDVs, Euro 4/5 motorcycles) are estimates only based on the emission limit reductions and expected technological developments.
- An effort has been made that the relative trends are reliable. This means that the qualitative relative impact (increase or decrease of emissions) when shifting from one technology or fuel to the other is reliable.
- When significant uncertainties or complete lack of information exists, this is clearly designated in the respective table.

6.2. Remaining environmental concerns

Persistent air quality problems in cities and the significant contribution of transport in urban inventories mean that vehicle air pollutant emission levels have to further decrease from current levels. Moreover, substantial GHG savings have been scheduled for road transport to warrant its sustainability and to alleviate dependence on imports of fossil fuels. These requirements create a demanding environment for regulation authorities and for the industrial stakeholders (manufacturers, fuel producers, operators, etc.) to deliver actual on-road emission reductions.

Past experience has shown that planned emission reductions by the regulations have not always made it to real-world emission levels. This has occurred both in the air pollutant and GHG fronts. There are two very characteristic examples. The first one has been the diesel Euro 5 passenger car exceedance of NO_x emission limits. Up to 3-5 times higher real-world emis-

sion levels than the emission limits have been established in several studies (Fontaras et al., 2014; Weiss et al., 2011b). The second example has been the failure of the GHG control regulations to deliver the planned reductions under realistic driving conditions. More than 60 % higher fuel consumption than the type approval value has been reported for some late model passenger cars, with the average deviation in the 11-16 % range (Ntziachristos et al., 2014).

It is currently well established that failure to deliver actual emission reductions of future vehicle types undermines the whole environmental policy at a European level (Borken-Kleeefeld and Ntziachristos, 2012). Further to the very significant health and environmental impacts this will have, this will also bring significant financial and legal implications to the member states. This is why current regulatory efforts aim at safeguarding that planned reductions in emissions with the upcoming Euro stages will be materialized. The introduction of strict OBD regulations, extended durability requirements, revised driving cycles that better simulate real world conditions, particle number control for diesel and gasoline cars, and the control of emissions with PEMS on-board the vehicle, are all regulatory tools which go into this direction.

Despite these substantial changes and revisions, the review conducted to develop the emission factors in this report identified several issues that still need to be addressed with regard to road vehicle emission control. These are summarized to the following points:

- Liquefied petroleum gas (LPG) and, to a lesser extent compressed natural gas (CNG) retrofits on existing gasoline vehicles are a widespread practice in several member states, as drivers aim at benefiting from the substantial price difference between LPG and gasoline. Retrofits are only approved by authorities for their safety and in terms of emission performance in oversimplified inspection and maintenance (I&M) tests. The latter have been designed to check whether original fuelled vehicles behave as they should and not to test whether alternative fuels deliver a similar performance level. Most importantly, NO_x emission levels are not at all checked in I&M tests. Evidence shows that the lambda sensor used for retaining stoichiometry may slightly drift when an alternative fuel is used, and by that significantly degrading the performance of emission control systems. It can now safely be considered that possible NO_x air quality problems from LPG (and CNG) retrofits are not at all recognised. More checks on retrofitted vehicles are required and depending on the extent of the problem, specific interventions need to be planned.
- Nitrous oxide (N₂O) emissions are not considered by current GHG regulations. Given the almost 300 times CO₂-equivalent of N₂O, even trace amounts in the tailpipe can substantially contribute to total GHG emissions from individual vehicles. There is evidence that some diesel deNO_x aftertreatment systems currently employed may substantially increase N₂O emissions. Combined to the decreasing tailpipe CO₂ levels, the relative contribution of N₂O increases. Evidence collected from literature sources shows that this may reach up to 5 % of CO₂ emissions from late model diesel passenger cars equipped with SCR. Including N₂O emissions in the total GHG policy budget is therefore necessary.
- Ammonia (NH₃) emissions contribute to photochemical pollution and secondary PM formation. Ammonia is only controlled for heavy duty vehicles equipped with SCR, at a 10 ppm tailpipe level. No provision has been made for SCR equipped light duty vehicles and,

therefore, NH_3 emission levels are not at all controlled from this vehicle category. This needs to be addressed. Most importantly, the limited measurements on spark-ignition vehicles demonstrate that NH_3 is mostly produced from degraded three-way catalysts. US experience from spark ignition buses operating on CNG has shown up to 1 g/km of NH_3 which suggests a potentially significant uncontrolled environmental problem. Aged gasoline vehicles also seem to be a problem. New Euro 6c GDI vehicles combining TWC+GPF technology need also to be studied in terms of their NH_3 emissions. Targeted NH_3 emission measurements from new and aged gasoline and gaseous fuelled vehicles are required to better understand the potential problem before interventions are planned.

- Particle number (PN) emission control is nowadays well established in Europe for all CI vehicle types and GDI ones. The strict limits enforced from 2017 on should guarantee effective control of solid particles for those vehicle types falling under this regulation. There is evidence that gasoline hybrid vehicles may produce relatively high solid particle numbers due to the intermittent engine operation while no information exists on possible particle number increase during the frequent starts of gasoline vehicles equipped with start and stop systems. While this is of worth exploring more because these vehicles are not covered by existing regulations, this behaviour is not considered to constitute a real environmental problem. On the other hand, the most significant omission of PN emission control policy in Europe has been the decision not to include the non-solid particulate phase in the regulation. Several studies have shown that all vehicle types, including gaseous fuelled vehicles, may produce high numbers of particles when their exhaust is diluted in atmospheric conditions. Such secondary particles can be formed in different time scales, from milliseconds to a few hours after emissions are exposed to the atmosphere. While in the past such studies received much attention, the decision to regulate solid PN has decreased the momentum regarding total particle number understanding and control. The perception that current regulations do the maximum which is technically feasible to control PM emissions need to be reconsidered, especially given the fact that ambient PM concentrations have not been falling as originally expected. Therefore, the large contribution of road traffic in (primary or secondary) particle concentrations in the urban environment is projected to continue in the future, unless a more holistic regulation of particle emissions is considered.
- Several pollutants for which air quality limits exist or for which there is a known toxic character still remain uncontrolled. As a result, limited or even no information is available and, consequently, the contribution of road transport to ambient concentrations of these pollutants may be misjudged. Particular examples include oxygenated species, like aldehydes and ketones, which are not part of the THC emissions considered by today's regulations, chlorinated species like HCB for which emissions need to be reported but no emission measurements are available, and particular HC species like benzene or benzo-a-pyrene for which knowledge on the impact of fuel properties and aftertreatment operation is very limited.

6.3. Priorities for future studies

All the items presented in the previous section need to be examined and gradually prioritised for future research studies and, if necessary, regulatory control. Out of the several directions that still remain for a holistic control of vehicle emissions, there are some key areas that require special attention:

- Recurring measurement campaigns are needed to verify that diesel passenger cars fulfilling the Euro 6 and, in particular, the Euro 6c standard deliver the designed reductions in terms of NO_x emissions, at least until the RDE regulation becomes mandatory. These campaigns can be done using real-world chassis dynamometer driving tests, PEMS road tests, remote sensing techniques, and any other tool that can identify emissions in the actual operation conditions of vehicles.
- The increasing gap between type-approval and real-world GHG and fuel consumption values for passenger cars with time needs to be reverted. There are currently on-going regulatory developments to change the driving cycle and the type-approval procedure, in order to try to close this gap. Until this becomes successful, independent studies and campaigns on the measurement of real fuel consumption from existing vehicle models need to be promoted. Customer information and market forces may then correct this trend faster and more reliably than regulatory efforts.
- In-use emissions of vehicles need to be given more attention. Emission levels at a fleet level may increase as the stock of vehicle grows older due to normal ageing of each individual vehicle, increase in the probability of emission control failures, and increase in the frequency of technical interventions (tampering, retrofitting, and use of not verified spare parts). There are several techniques that are used and can be improved to more efficiently control in-use emission levels. First, there is little information on the effectiveness of OBD. Information on the type and frequency of failures detected, their impact on emission level and schemes to link OBD monitoring with inspection and maintenance practices need to be developed. The inspection and maintenance emission tests themselves need to be refined because they are still designed around Euro 1 vehicles. A more elaborate testing procedure and inclusion of NO_x as part of the monitored pollutants would be revisions in the desired direction. Finally, retrofitting vehicles with alternative fuel kits should ideally require a new type-approval or at least be thoroughly checked (e.g. with PEMS) on whether emissions continue to comply with the designated emission standard.
- Non-regulated pollutants and the impacts of new aftertreatment technologies and alternative fuels on their emission levels need to be better understood. VOC speciation, as well as N₂O and NH₃ emission levels have to be studied. Depending on the results, regulatory efforts to control the emissions of some additional pollutants may be required.

As a concluding remark, it has to be highlighted that despite the attention and the many research efforts to understand, monitor and control vehicle emissions, there are still significant unknowns. These come from the variety of technologies and fuels on the road, the often change of technology (every 4-5 years) and the range of environmental and driving

conditions that vehicles operate in. Efforts should continue to develop better emission factors. These will be used to develop better inventories, understand and predict urban air quality hotspots and, in the end, design more effective policy. Hence, all investment that goes into the development of emission factors pays off by improved air quality, decreased environmental and health impacts and therefore a substantial reductions in the external costs of transport.

Definitions and Abbreviations

AECC	Association for Emissions Control by Catalyst	GRPE	Working party on pollution and energy
BEV	Batter Electric Vehicle	GSI	Gear Shift Indicator
CADC	Common Artemis Driving Cycles	GTL	Gas-To-Liquid
CDPF	Catalytic Diesel Particle Filter	HC	Hydrocarbon
CI	Compression Ignition	HCB	Hexachlorobenzene
CNG	Compressed Natural Gas	HDV	Heavy Duty Vehicles
CO	Carbon Monoxide	ICCT	The International Council on Clean Transportation
CO ₂	Carbon Dioxide	IEA-AMF	International Agency Association Advanced Motor Fuels Implementing Agreement
CONCAWE	The oil companies' European association for environment, health and safety in refining and distribution	I&M	Inspection and Maintenance
DG-JRC	Directorate General Joint Research Centre	IUPR	In-Use Performance Ratio
DME	Dimethylether	LAT	Laboratory of Applied Thermodynamics
DOC	Diesel Oxidation Catalyst	LCV	Light Commercial Vehicles (N1)
EC	European Commission	LDV	Light Duty Vehicles (L, M1, N1)
EEA	European Environment Agency	LNG	Liquefied Natural Gas
EEC	European Economic Commission	LNT	Lean NO _x Trap
EEV	Enhanced Environmentally friendly Vehicles	LPG	Liquefied Petroleum Gas
EGR	Exhaust Gas Recirculation	MCWG	MotorCycle Working Group
ELR	European Load Response	MIL	Malfunction Indicator Lamp
ERMES	European Research group on Mobile Emission Sources	MtOH	Methanol
ESC	European Stationary Cycle	MVEG	Motor Vehicle Emission Group
ETC	European Transient Tests	NEDC	New European Driving Cycle
EU	European Union	NMOG	NonMethane Organic Gas
FCEV	Fuel Cell Electric Vehicle	NMVOC	NonMethane Volatile Organic Compound
FGB	First Generation Biofuel	NG	Natural Gas
FID	Flame Ionization Detector	NO _x	Nitrogen Oxides
FP	Framework Programme	OBD	On Board Diagnostics
GDI	Gasoline Direct Injection	OEM	Original Equipment Manufacturer
GFV	Gaseous Fuelled Vehicle	OTL	OBD Threshold Limits
GHG	GreenHouse Gas	PC	Passenger Cars (M1)

PEMS	Portable Emission Measurement Systems
PFI	Port Fuel Injection
PI	Positive Ignition
PM	Particulate Matter
PMP	Particle Measurement Programme
PN	Particle Number
RDE	Real Drive Emissions
RSD	Remote Sensing Device
SCR	Selective Catalytic Reduction
SGB	Second Generation Biofuel
THC	Total Hydrocarbon Compounds
TOG	Total Organic Gas

TPM	Tyre Pressure Monitor
TUG	Technical University Graz
TWC	Three Way Catalyst
UNECE	United Nations Economic Commission for Europe
VOC	Volatile Organic Compound
WHSC	Worldwide Harmonised Steady state Cycle
WHTC	Worldwide Harmonised Transient Cycle
WLTP	Worldwide harmonized Light vehicles Test Procedure
WMTC	Worldwide harmonized Motorcycle emissions Certification Test procedure

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Annex:

Summary of emission factors proposed in this study

Vehicle Type	Emission Standard	Fuel	Concept	Driving Mode	CO (g/vkm)	HC (g/vkm)	NO _x (g/vkm)	N ₂ O (g/vkm)	NH ₃ (g/vkm)	NO ₂ /NO _x (wt)	PM ₁₀ (g/vkm)	PN (x10 ¹¹ /vkm)
Car	Euro 6	Gasoline	PFI	Urban	0.906	0.194	0.081	0.0025	0.007	0.050	0.0005	3.6
Car	Euro 6	Gasoline	PFI	Rural	0.688	0.014	0.025	0.0002	0.008	0.050	0.0005	3.1
Car	Euro 6	Gasoline	PFI	Highway	1.129	0.019	0.015	0.0010	0.022	0.050	0.0012	1.3
Car	Euro 6	Gasoline	DGI	Urban	0.906	0.194	0.081	0.0025	0.007	0.050	0.0010	20.0
Car	Euro 6	Gasoline	DGI	Rural	0.688	0.014	0.025	0.0002	0.008	0.050	0.0010	11.0
Car	Euro 6	Gasoline	DGI	Highway	1.129	0.019	0.015	0.0010	0.022	0.050	0.0025	7.5
Car	Euro 6	Diesel		Urban	0.085	0.050	0.304	0.0100	0.007	0.300	0.0027	9.3
Car	Euro 6	Diesel		Rural	0.055	0.040	0.286	0.0040	0.007	0.300	0.0015	3.7
Car	Euro 6	Diesel		Highway	0.066	0.029	0.433	0.0040	0.007	0.300	0.0014	2.6
Car	Euro 6	Gasoline	Hybrid	Urban	0.630	0.180	0.012	0.0025	0.007	0.050	0.0010	1.0
Car	Euro 6	Gasoline	Hybrid	Rural	0.035	0.004	0.001	0.0002	0.008	0.050	0.0010	5.0
Car	Euro 6	Gasoline	Hybrid	Highway	0.019	0.004	0.023	0.0010	0.022	0.050	0.0010	11.0
Car	Euro 6	Diesel	Hybrid	Urban	0.084	0.049	0.300	0.0100	0.007	0.300	0.0026	9.3
Car	Euro 6	Diesel	Hybrid	Rural	0.005	0.040	0.280	0.0040	0.007	0.300	0.0013	3.7
Car	Euro 6	Diesel	Hybrid	Highway	0.066	0.029	0.430	0.0040	0.007	0.300	0.0013	2.6
Car	Euro 6	LPG	OEM	Urban	0.850	0.170	0.080	0.0025	0.007	0.050	0.0005	3.6
Car	Euro 6	LPG	OEM	Rural	0.610	0.012	0.025	0.0002	0.008	0.050	0.0005	3.1
Car	Euro 6	LPG	OEM	Highway	1.040	0.012	0.014	0.0010	0.022	0.050	0.0012	1.3
Car	Euro 6	LPG	Retrofitter	Urban	0.850	0.170	0.192	0.0025	0.007	0.050	0.0005	3.6
Car	Euro 6	LPG	Retrofitter	Rural	0.610	0.012	0.060	0.0002	0.008	0.050	0.0005	3.1
Car	Euro 6	LPG	Retrofitter	Highway	1.040	0.012	0.034	0.0010	0.022	0.050	0.0012	1.3
Car	Euro 6	CNG	OEM	Urban	0.850	0.184	0.080	0.0025	0.007	0.050	0.0005	3.6
Car	Euro 6	CNG	OEM	Rural	0.610	0.060	0.025	0.0002	0.008	0.050	0.0005	3.1
Car	Euro 6	CNG	OEM	Highway	1.040	0.060	0.014	0.0010	0.022	0.050	0.0012	1.3
Car	Euro 6	CNG	Retrofitter	Urban	0.850	0.184	0.280	0.0025	0.007	0.050	0.0005	3.6
Car	Euro 6	CNG	Retrofitter	Rural	0.610	0.060	0.088	0.0002	0.008	0.050	0.0005	3.1
Car	Euro 6	CNG	Retrofitter	Highway	1.040	0.060	0.049	0.0010	0.022	0.050	0.0012	1.3

Vehicle Type	Emission Standard	Fuel	Concept	Driving Mode	CO (g/vkm)	HC (g/vkm)	NO _x (g/vkm)	N ₂ O (g/vkm)	NH ₃ (g/vkm)	NO ₂ /NO _x (wt)	PM ₁₀ (g/vkm)	PN (x10 ¹¹ /vkm)
HDV	Euro 6	Diesel	OEM 42t	Rural	0.300	0.020	0.240	0.0190	0.009	0.300	0.0130	1.5
HDV	Euro 6	Diesel	OEM 42t	Highway	0.100	0.010	0.210	0.0190	0.009	0.300	0.0110	1.0
Bus & Coach	Euro 6	Diesel	OEM 15t	Urban	0.520	0.030	0.850	0.0150	0.009	0.300	0.0090	1.2
Bus & Coach	Euro 6	Diesel	OEM 15t	Rural	0.130	0.020	0.220	0.0150	0.009	0.300	0.0030	0.4
Bus & Coach	Euro 6	Diesel	OEM 15t	Highway	0.170	0.010	0.210	0.0150	0.009	0.300	0.0030	0.5
Urban Bus	EEV	Diesel	EGR	Urban	0.200	0.010	7.000	0.0500	0.001	0.150	0.0420	2000
Urban Bus	EEV	Diesel	EGR +non cat DPF	Urban	0.200	0.010	7.000	0.0500	0.001	0.150	0.0110	1.5
Urban Bus	EEV	Diesel	EGR +cat DPF	Urban	0.200	0.010	7.000	0.0500	0.001	0.360	0.0110	1.5
Urban Bus	EEV	Diesel	SCR	Urban	0.100	0.010	5.700	0.2000	0.040	0.100	0.0420	2000
Urban Bus	EEV	Diesel	SCRT	Urban	0.100	0.010	5.700	0.2000	0.040	0.100	0.0110	1.5
Urban Bus	EEV	CNG	Stoi chiometric +TWC	Urban	1.000	0.800	1.500	0.0300	1.000	0.025	0.0110	1.5
Urban Bus	EEV	CNG	Lean Burn +Ox. Cat.	Urban	0.150	2.000	6.700	0.0300	0.050	0.400	0.0180	1.5
Urban Bus	EEV	EtOH	TWC	Urban	0.010	0.430	5.500	0.0400	0.001	0.035	0.0360	1700
Moped	Euro 3	Gasoline	2-stroke	Urban	1.800	2.050	0.170	0.0020	0.005	0.050	0.0180	300
Moped	Euro 3	Gasoline	4-stroke	Urban	2.700	0.790	0.170	0.0020	0.015	0.050	0.0040	80
Motorcycled	Euro 3	Gasoline	2-stroke	Urban	2.100	0.580	0.010	0.0020	0.005	0.050	0.0050	90
Motorcycled	Euro 3	Gasoline	4-stroke	Urban	2.400	0.240	0.150	0.0020	0.020	0.050	0.0020	12
Micro-car	Euro 2	Diesel	4-stroke	Urban	0.930	0.150	0.810	0.0030	0.001	0.110	0.1500	2000
Car	Euro 6c	Diesel		Urban	0.085	0.050	0.160	0.0150	0.010	0.300	0.0027	9.3
Car	Euro 6c	Diesel		Rural	0.055	0.040	0.150	0.0055	0.010	0.300	0.0015	3.7
Car	Euro 6c	Diesel		Highway	0.066	0.029	0.230	0.0055	0.010	0.300	0.0014	2.6
Moped	Euro 4	Gasoline	4-stroke	Urban	1.800	1.100	0.170	0.0020	0.015	0.050	0.0050	100
Moped	Euro 5	Gasoline	4-stroke	Urban	1.500	0.170	0.060	0.0020	0.020	0.050	0.0008	3.0
Motorcycled	Euro 4	Gasoline	4-stroke	Urban	1.300	0.180	0.072	0.0020	0.020	0.050	0.0025	3.0
Motorcycled	Euro 5	Gasoline	4-stroke	Urban	1.100	0.090	0.048	0.0020	0.020	0.050	0.0007	3.0
Micro-car	Euro 4	Diesel	4-stroke	Urban	0.470	0.080	0.690	0.0050	0.001	0.200	0.0800	1500
Micro-car	Euro 5	Diesel	4-stroke	Urban	0.230	0.080	0.150	0.0100	0.001	0.400	0.0030	6.0

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